Fatigue Crack Growth & Testing Committee

2026 ERSI Workshop

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ENGINEERED RESIDUAL STRESS IMPLEMENTATION

Outline for this 3 hour session

- Introduction, summary and overview (20 mins)
- Updates, achievements and plans from Focus Areas
  - IFF and 2025 A-10 Cx Dataset (Bob/Jake – 40 mins)
  - 7050-T7451 Cx hole spectrum loading test and analysis lessons learned (Kevin - 10 mins)

- Break (10 mins)

- Updates, achievements and plans from Focus Areas
  - Spectrum Loading (Moises - 15 mins)
  - Durability and Exact SIF Solution approach (Adrian – 20 mins)
- Lincoln Wheel Update (Bob – 20 mins)

- Break (10 mins)

- Discussion (All – 30 mins)

Outline of this presentation

- Roster summary
- Vision: Mission and key objectives
- Implementation roadmap
- Focus areas and working groups

Roster Summary

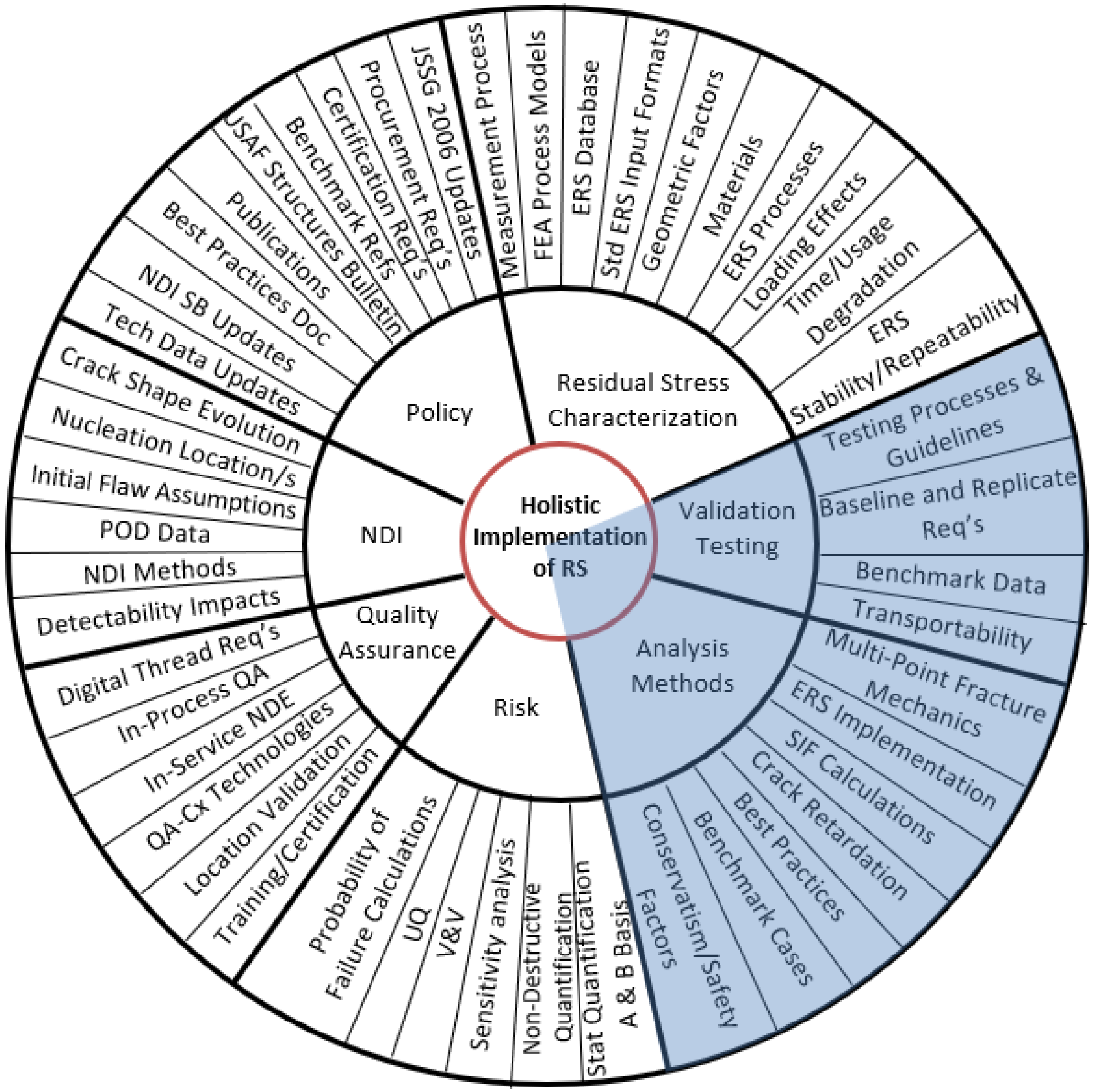
- **Committee members**
  - 71 members (down slightly from 75 last year – several retirements etc.)
  - Diverse participation from government, OEMs, small businesses, and academia
- **Active participants**
  - ~10-15 participants in monthly meetings
- **Working groups**
  - Three working groups
    - Spectrum loading
      - Leads – Moises, Walker
      - Participants ~ 7 members
      - Rolled into main monthly meetings for now
    - Interference fit fasteners
      - Leads – Pilarczyk, Loghin, Ribeiro
      - Participants ~ 19 members
    - Durability and fatigue life benefits
      - Lead – Adrian Loghin
      - On hold for now, but may get this going

Vision

- **Mission statement**
  - Establish **analytical and testing guidelines** to support the implementation of engineered residual stresses
- **Key objectives**
  - Develop and document **best practices** for the integration of engineered residual stresses into fatigue crack growth prediction methodologies
  - Establish **testing requirements** considering the impacts of residual stress on fatigue crack growth
  - Develop **datasets and case studies** to support analysis methods validation
  - Identify, define, and enable the **resolution of gaps** in the analytical methods state-of-the-art
  - Support the development of an **implementation roadmap**

Implementation Roadmap

- **Approach**
  - Leverage ASIP Lincoln Wheel
  - Tailored for ERS
  - Identify key focus areas
  - Highlight focus areas based on criticality and maturity
- **Benefits**
  - Utilize to communicate development needs



Focus Areas

- **Spectrum loading and retardation (active)**
  - Investigate the appropriate methods to characterize crack retardation due to spectrum loading for conditions with residual stress
  - Gather and/or develop test data to support validation of methods
  - Document best practices and lessons learned
- **Interference fit fasteners (IFF) and residual stress (active)**
  - Investigate the relationship between interference fit fasteners and residual stresses from Cx and/or Taper-Lok
  - Identify appropriate methods to incorporate interference fit fastener benefit for conditions with residual stress
  - Document best practices and lessons learned
- **Durability testing and fatigue life benefits (now active)**
  - Review existing test data and develop summary to document Cx life impacts on early crack nucleation and growth
  - Identify any testing needs to further refine understanding

Spectrum Loading Working Group

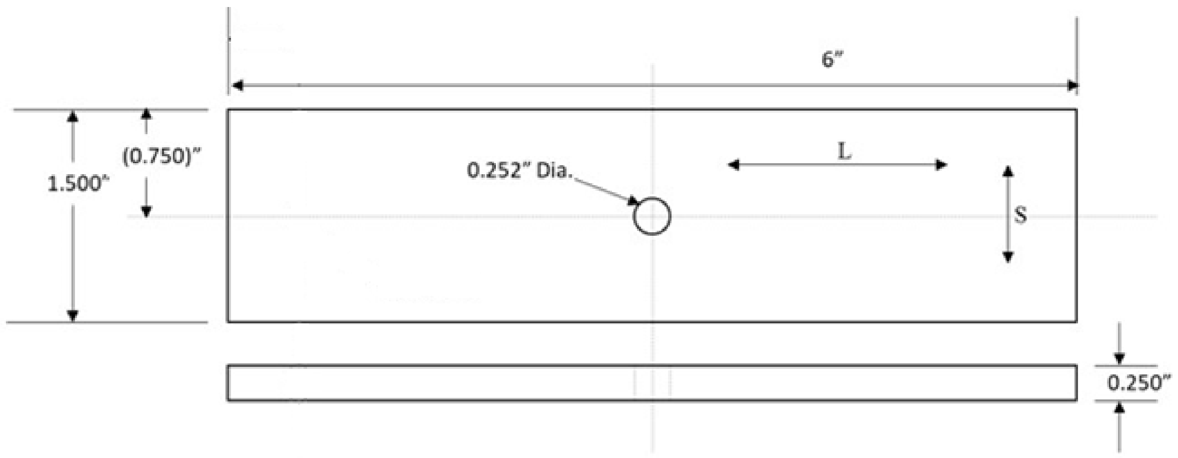
- **Participation**
  - ~ 10 members
- **Objectives**
  - Collaborate to understand load interaction effects on crack growth using simple spectrum loading (spike overload) and spectrum loading. Validate and understand limitations of proposed modeling for plastic tip constraint loss.
- **Approach**
  - Perform blind predictions with various analysis tools and retardation approaches
  - Develop validation test data to compare/contrast with analysis predictions
- **Key collaboration areas**
  - Spike Overload Testing (Boeing & QinetiQ Australia/Mississippi State) (Mainly covered last year)
  - Review and lessons learned from DSTG Australia 7050-T7451 Cx hole under spectrum loading with natural crack initiation (Kevin)
  - Develop guidelines for considering spectrum loading effects based on lessons learned to date (Moises)

Spectrum Loading Effects Guidelines

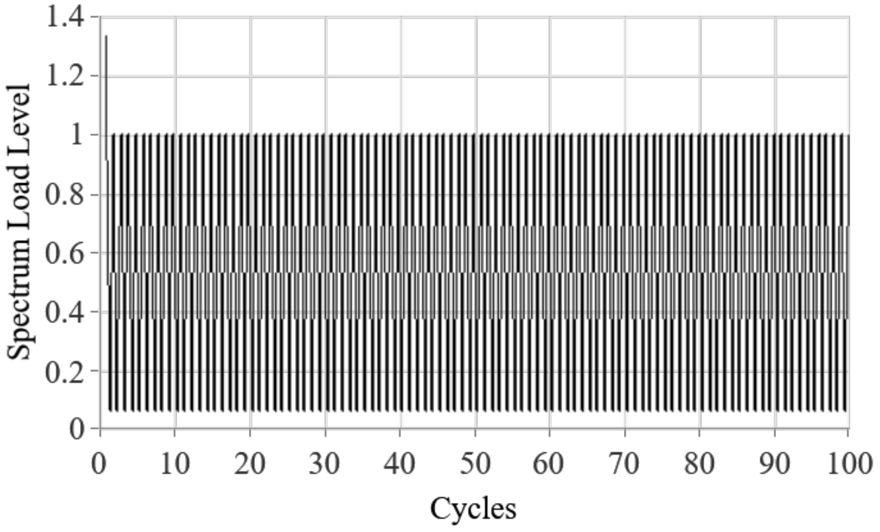
- Consolidate information:
  - Literature review
  - Lessons learned
  - Available case studies (e.g., DST Assist Wide Plate Spectrum Challenge)
- Identify challenges
  - Prediction with Cx residuals is highly sensitive to Region I FCGR
  - Difficulties in modeling constraint: thru crack vs. part-thru crack constraint differences, tension-compression loading effects, and determining the presence of constraint loss
- Consolidate Best Practices
  - R_{eff} interaction models (e.g., Willenborg)
  - K_{op} interaction models (e.g., Strip Yield)
- Identify limits of approach in case studies
  - Sensitivity Studies: life-prediction variability due to growth-rate fit, model sensitivity to constraint factor estimate
  - Guidelines on limiting crack closure benefits for edge cases (e.g.; identify applicability limits for large-scale yielding and other edge-case conditions)

Revisiting Boeing IRAD Shakedown Test

- Alloy: Ti-6Al-4V RA Forging
- Grain Direction: L-S
- Yield Strength: 131 ksi
- Max Stress: 28 ksi (L1), 42.1 ksi (L2), 56.1 (L3)
- Constant amplitude loading (R = 0.06) with 1.33 overload at the beginning of the test



Open Hole Specimen



Test Spectrum

Revisiting Boeing IRAD Shakedown Test (cont.)

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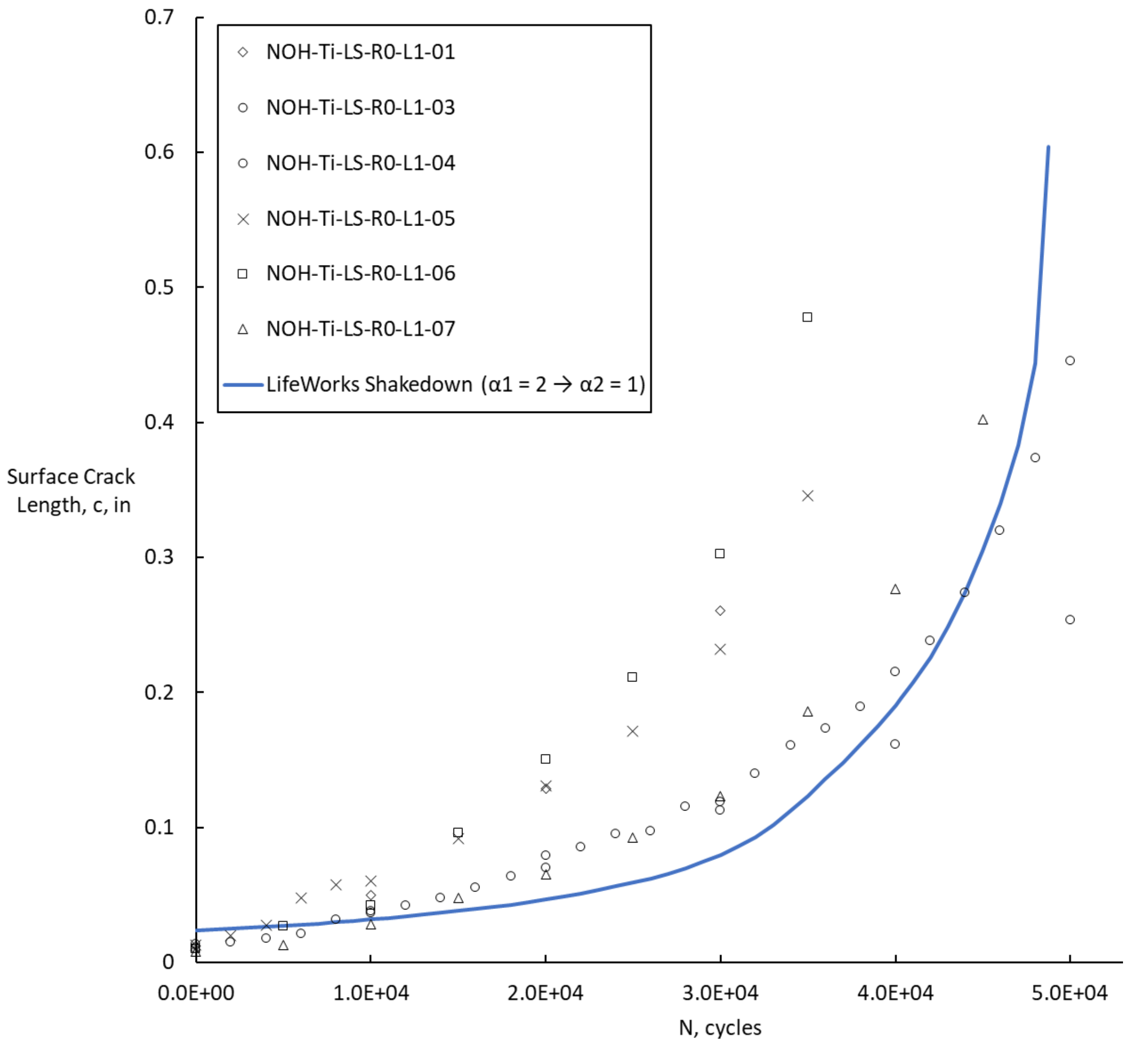
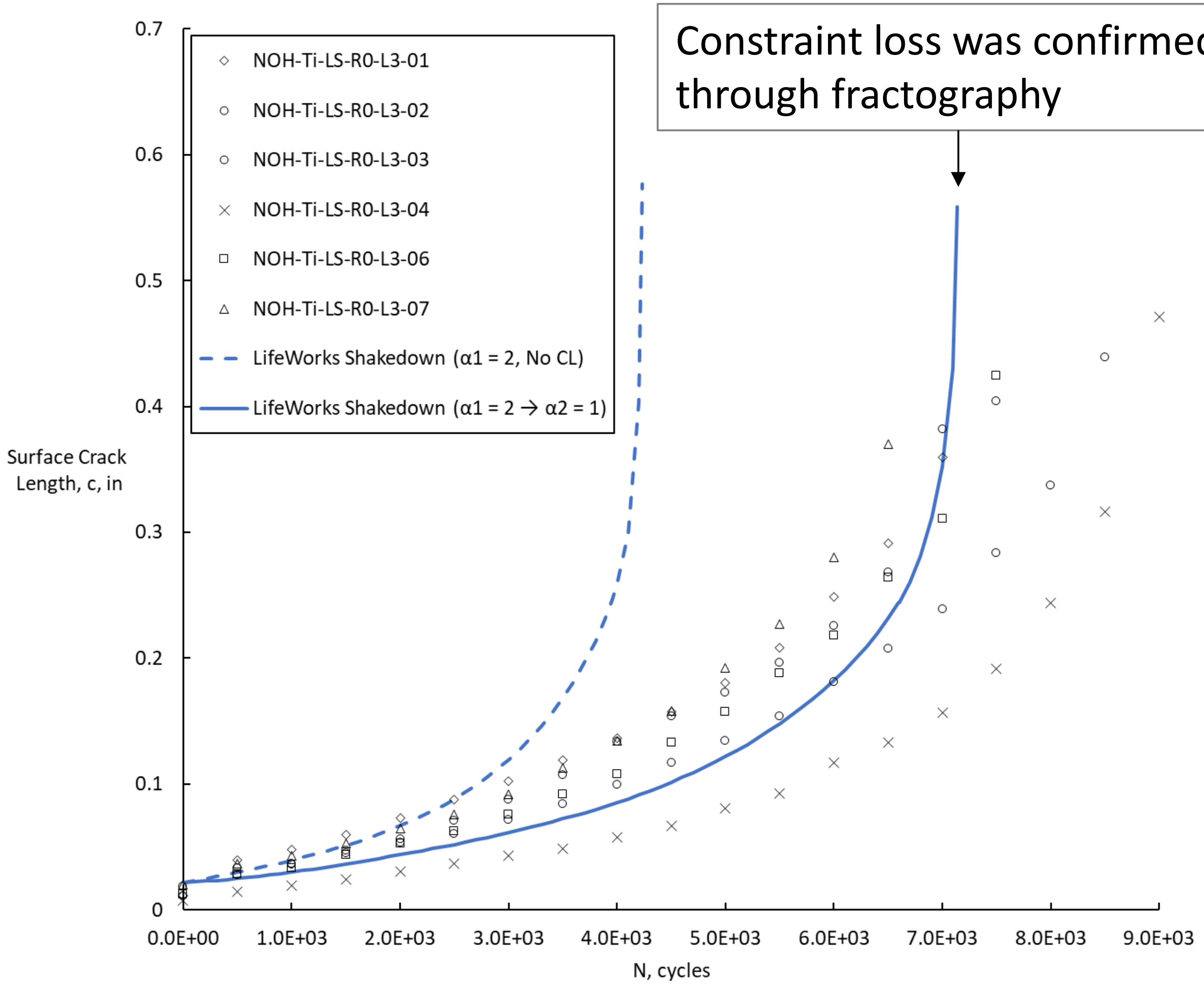
Max Stress = 28 ksi



Max Stress = 56.1 ksi

Constraint loss was confirmed through fractography



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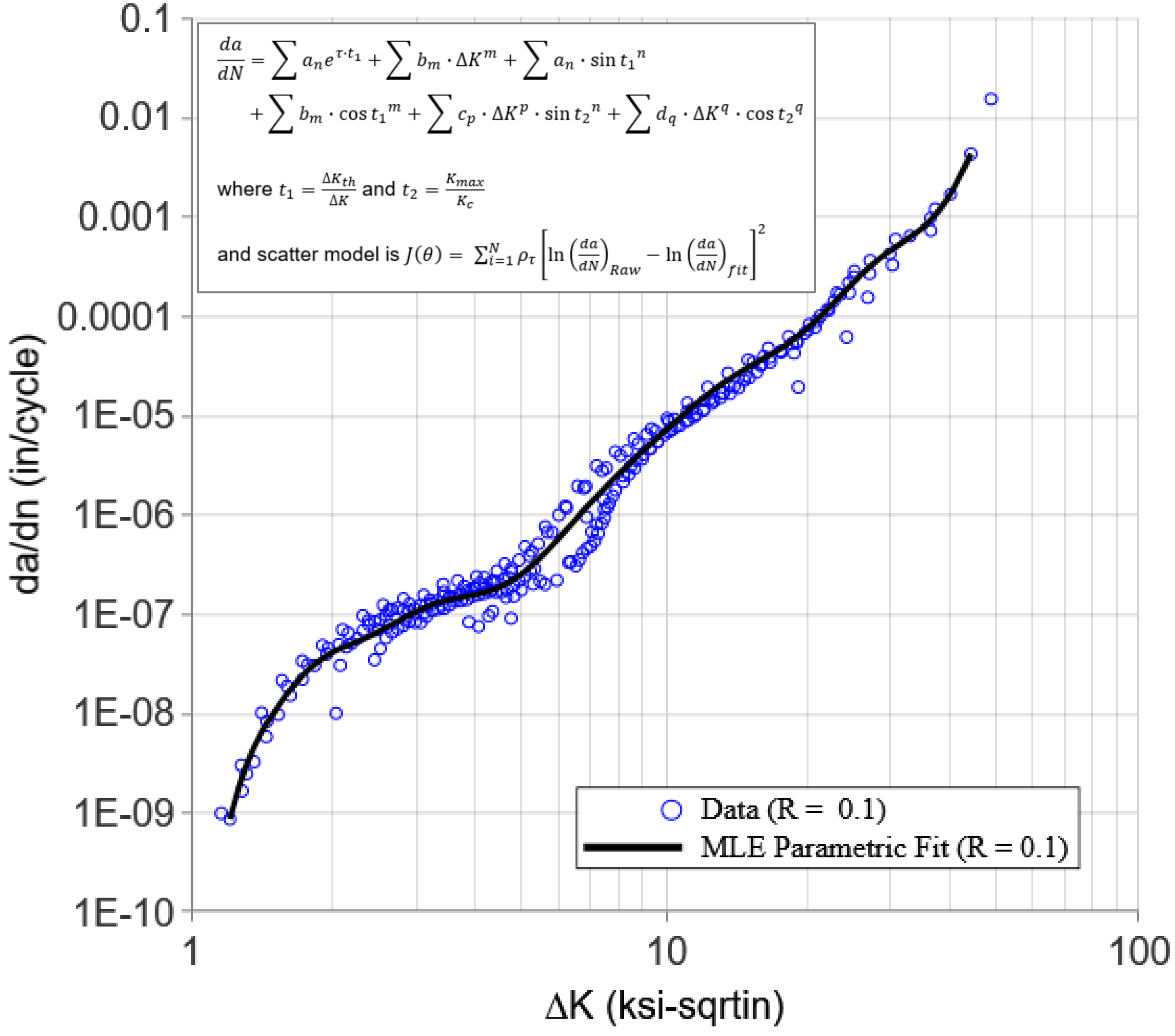
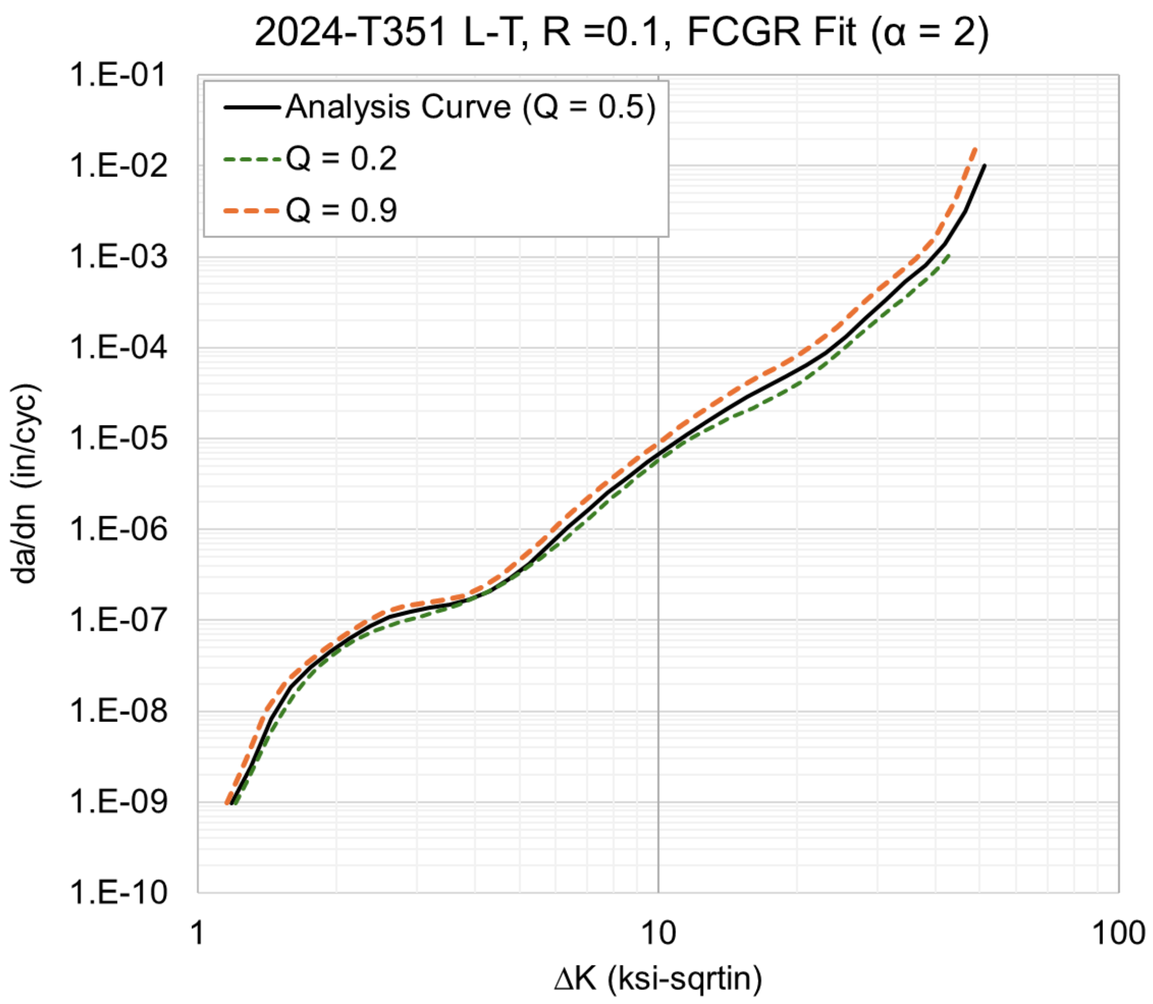
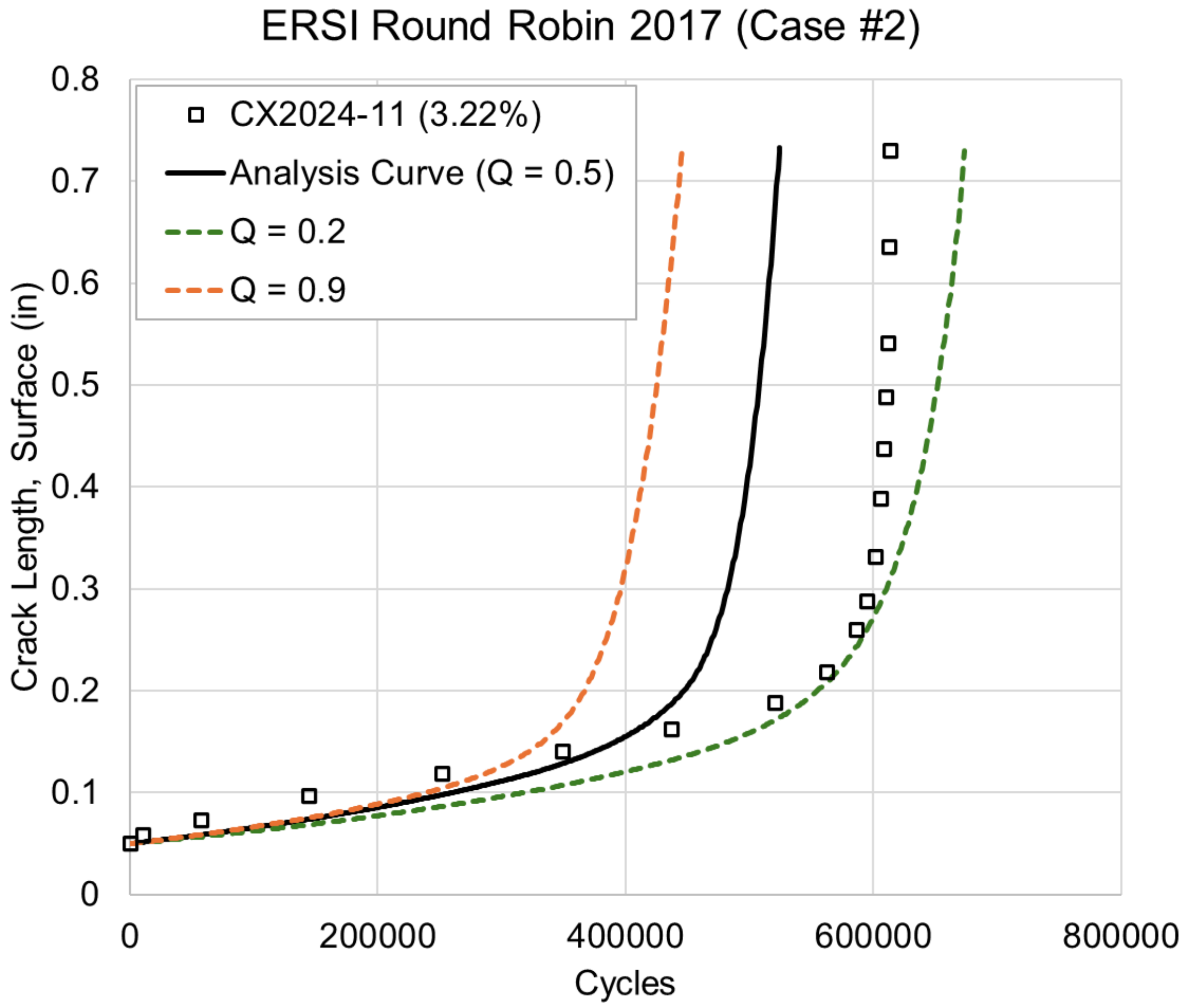
Sensibility Study: 2017 Cx Round Robin

- Data from different sources
  - AFMAT (available here)
  - Others (Hudson, Dubenski, Oldersma-Wanhill)
- Constraint factor of 2
- Assuming constraint loss
- FCGR Region-I forced to R = 0.8 data after collapsing (ΔK_{eff}) due to lack of compression pre-cracked FCGR data.

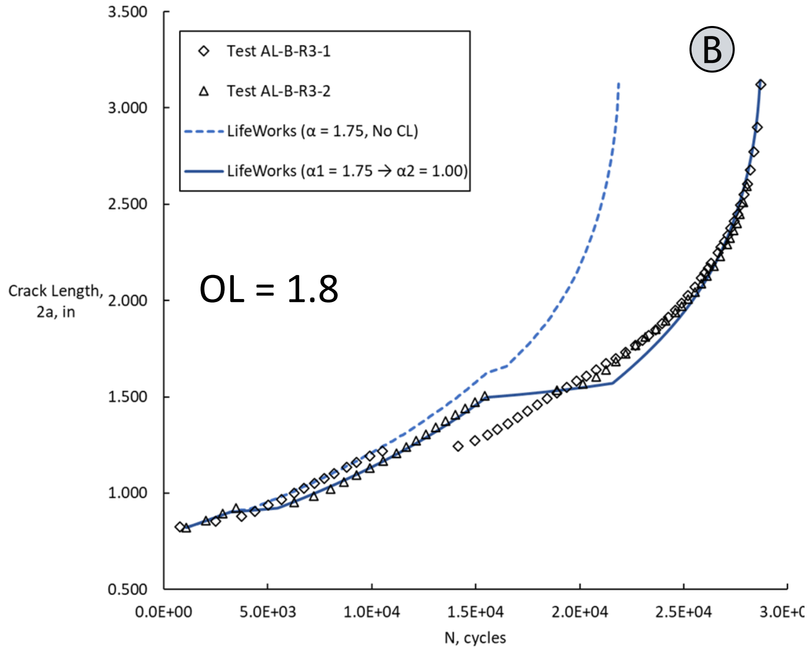


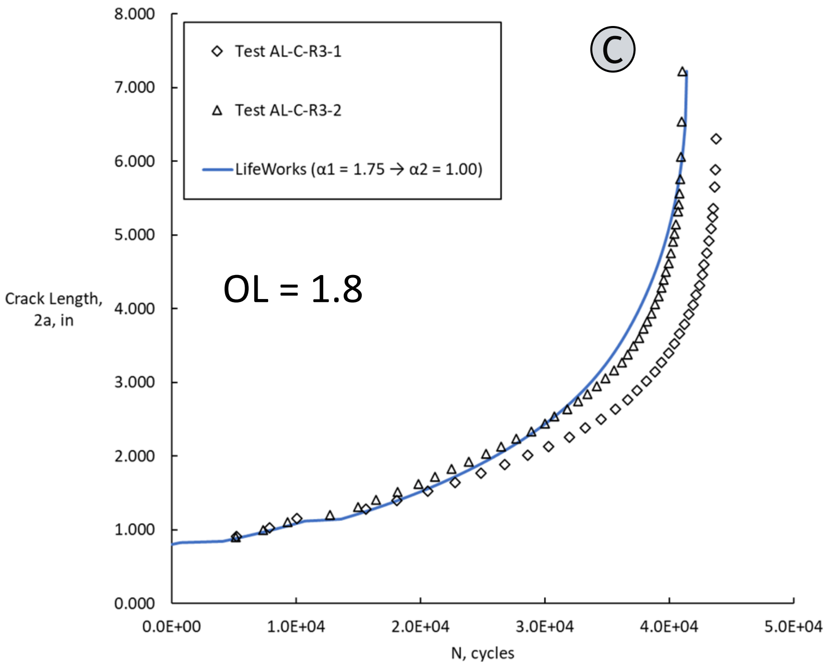
Sensibility Study: 2017 Cx Round Robin (cont.)

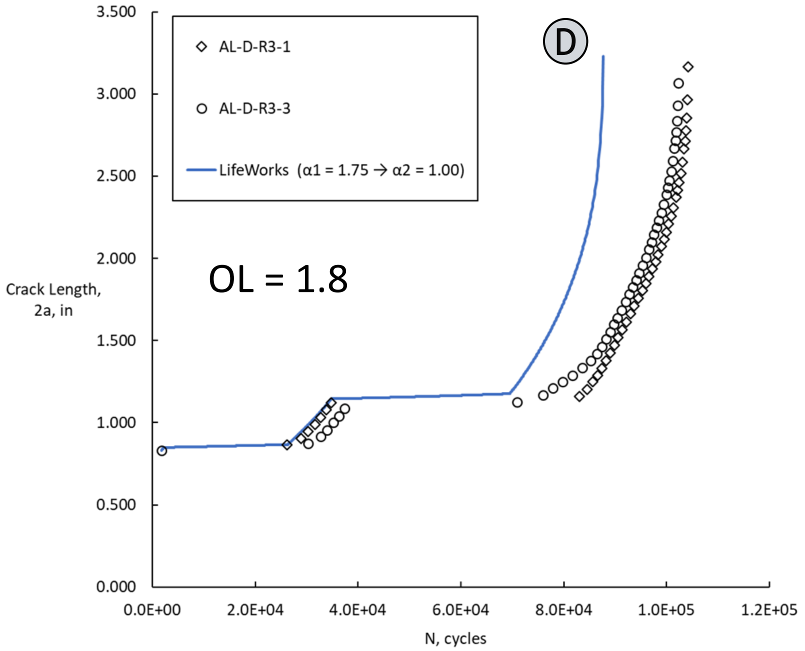




Revisiting 7075-T6 Spike Overload (Boeing)





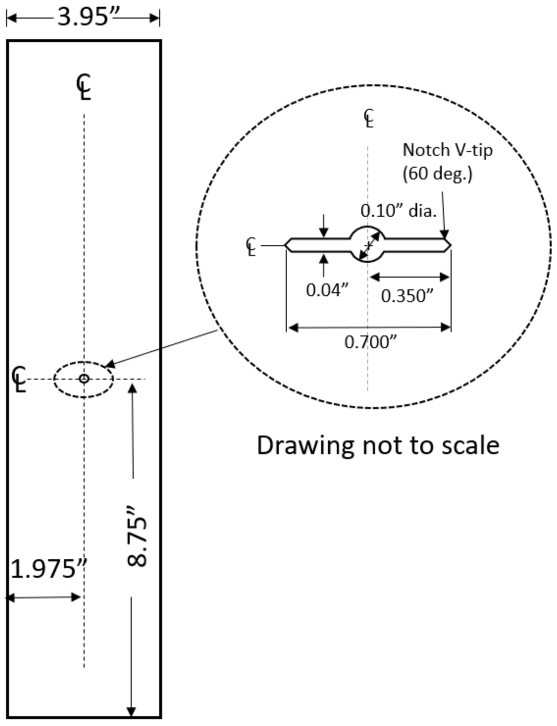


- Ⓐ Growth Rate Characterization
- Ⓑ Constraint Loss
- Ⓒ Constraint Loss Width Effects
- Ⓓ Constraint Loss Thickness Effects

Configuration	Task No.	No. of specimens	Starter notch type	Width, in.	Height, in.	Thickness, in.	Additional Instrumentation
A	1	8	EDM[1]	3.95	17.5	0.19	CMOD gauges[3]
B	2	3	EDM[2]	3.95	17.5	0.09	CMOD gauges[3]
C	3	3	EDM[2]	10	26	0.09	CMOD gauges[3]
D	4	3	EDM[2]	3.95	17.5	0.19	CMOD gauges[3]

Revisiting 7075-T6 Spike Overload (Boeing)

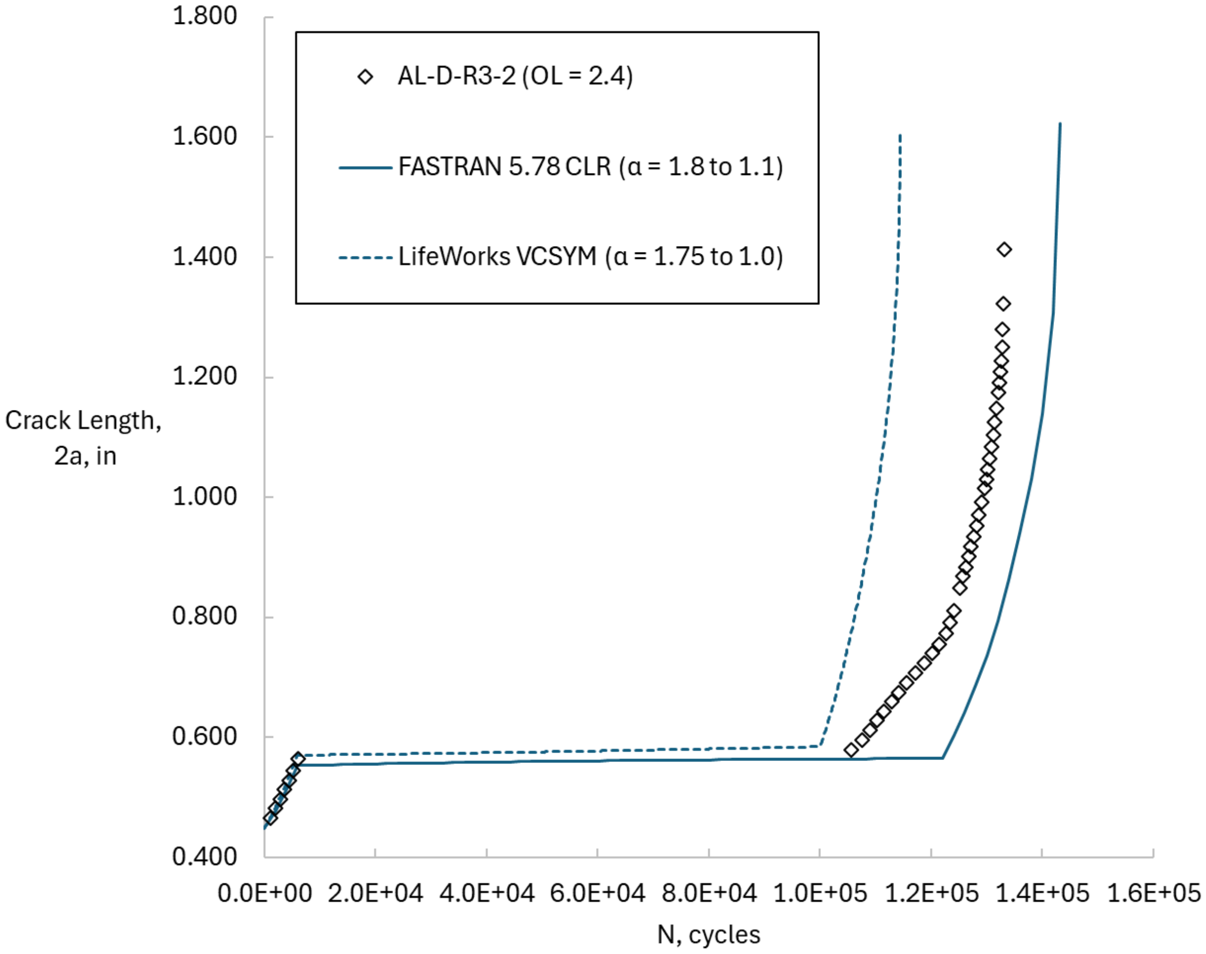
- What about large overloads?



Drawing not to scale

thickness = 0.19 in

7075-T6, Pmax = 6.75 kips, R = 0.01, OL = 2.4



Some publications – Spectrum Loading

- **Spectrum loading constraint-loss**

  Highlighted publication not included last year, previous publications shown "greyed out" as follows:

  - J.C. Newman, J.C., Walker, K.F., Fatigue crack growth under single-spike overloads-underloads and a simulated aircraft spectrum, Engineering Fracture Mechanics, (2025).
  - *Walker, K.F., et al., Simulation of fatigue crack growth in aluminium alloy 7075-T7351 under spike overload and aircraft spectrum loading. International Journal of Fatigue, 2025. 190: p. 108660.*
  - *Newman, J.C. and K.F. Walker, Fatigue Crack Growth on Several Materials under Single-Spike Overloads and Aircraft Spectra during Constraint-Loss Behavior. Materials Performance and Characterization, 2024. 13(2).*
  - *Newman , J.C., Jr., and Walker, K.F., Fatigue Crack Growth in 7075-T6 Aluminium Alloy Under Single-Spike Overloads and Aircraft Spectra, in Variable-Amplitude Loading (VAL5). 2024: Dresden, Germany.*
  - *Newman , J.C., Jr., and Walker, K.F., Fatigue crack growth on several materials under single spike overloads and aircraft spectra, in International Committee on Aeronautical Fatigue. 2023: Delft, The Netherlands.*

IFF Working Group

- **Participation**
  - 13 members
- **Objective**
  - Collaborate to establish validated analytical methods for Interference Fit Fasteners (IFF)
    - Review Physics of Interference Fit Fastener
    - Characterize Existing Methods & Data
    - Identify Key Factors and Gaps in Current Methods/Data
- **Approach**
  - Phased approach with increasing complexity
    - Phase I: Baseline stress analysis verification
    - Phase II: Stress intensity factor comparisons
    - Phase III: Crack growth analyses comparisons
  - Validation tests sponsored by A-10 team to accompany analyses
- **Key collaboration areas**
  - IFF Analysis Round Robin (Pilarczyk, Loghin, Ribeiro)
  - A-10 IFF Testing & Analysis Program (Warner, Smith)

Accomplishments IFF

- **ERSI IFF Analysis Round Robin**
  - Predictions received for baseline stress analysis
  - Eight different participants utilizing five different software packages
  - Phase I analysis and test comparisons complete
  - Phase II and III on hold awaiting test details from A-10 program
- **A-10 IFF Testing**
  - Stress characterization: complete
    - DIC characterization of the fit conditions (OH, NF, 0.3%, 0.6%, and 1.2%)
    - Report submitted
  - Fatigue testing: in progress
    - APES and SwRI performing the fatigue testing
      - APES: R= 0.02 and 0.6
      - SwRI: R= -1 and spectrum loading history (A10 CP7)
    - Approximately 50% complete with both labs actively testing
- **Publications**
  - Ribeiro, R.L., et al., Interference Fit Fasteners: A Finite Element Process Modeling Round Robin. Materials Performance and Characterization, 2025. (in coordination for publication)
  - Pilarczyk, R.T., et al., Testing & Analysis of Interference Fit Fasteners: An A-10 ASIP & ERSI Joint Effort. 2024 USAF ASIP Conference Proceedings.

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Durability and Fatigue Life Test Working Group

- **Participation: 1 (Adrian)**
- **Objective:**
  - Extend our understanding and modeling capabilities beyond long crack behavior
- **Approach**
  - It is not clear what would be the best initial approach. It was suggested in a previous Tcon to investigate the 0.005 inch initial crack size usage in different damage tolerance practices. If this is a desired goal of this working group, we could define some approaches that could be accomplished.
  - Any feasible approach would include a collaboration between various expertise domains: modeling, testing, material characterization, NDE.
- **Key collaboration areas (very general)**
  - Short crack behavior, measurement, modeling
  - Microstructural small crack measurement and modeling
  - Microstructure characterization, reconstruction, crystal plasticity, ...

Future Plans

- **Key focus areas for 2025-2026**
  - **To be discussed at this Workshop**

Summary

- **Diverse, active committee focused on key aspects for accurate analytical predictions with supporting validation data**
- **Topic areas have expanded beyond Cx since the original round robin**
  - Areas are critical for practical application
- **Refocusing on Cx cases is important moving forward**
  - Address differences between predictions and tests
  - Incorporate effects of IFF and spectrum

A-10 Cx Dataset: ERSI Blind Predictions

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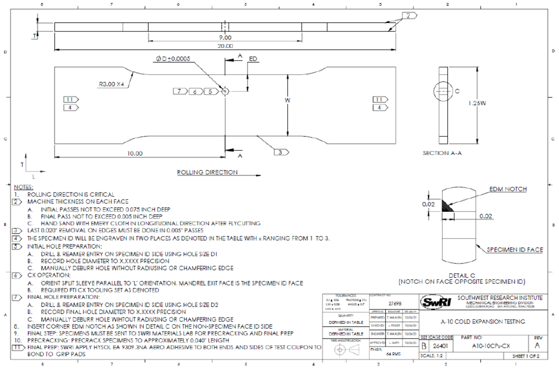
New A-10 Cx Testing

- **Purpose**
  - The A-10 program is transitioning toward using residual stresses from cold expansion directly in damage tolerance analyses. A test program was developed to target and isolate the load history and residual stress effects for Cx holes. Fatigue tests include baseline non-Cx and Cx holes, constant amplitude and spectrum loading, and are complimented with residual stress measurements for each condition
- **Test Data**
  - Testing and fractography completed by SwRI and APES

New A-10 Cx Testing, Constant Amplitude Tests

- Input Data
  - Geometry
    - Various (see table)
  - Material
    - Various (see table)
  - Starting flaw
    - Notched, pre-cracked, and final reamed
  - Cx conditions
    - Baseline non-Cx and Cx holes
  - Loading
    - Constant amplitude w/ markerbands
    - Max stresses = 23 and 25 ksi
    - Stress ratio = 0.1, 0.15

Material
7075-T76511 extrusion
2024-T351 plate
2024-T3511 extrusion
7075-T651 plate

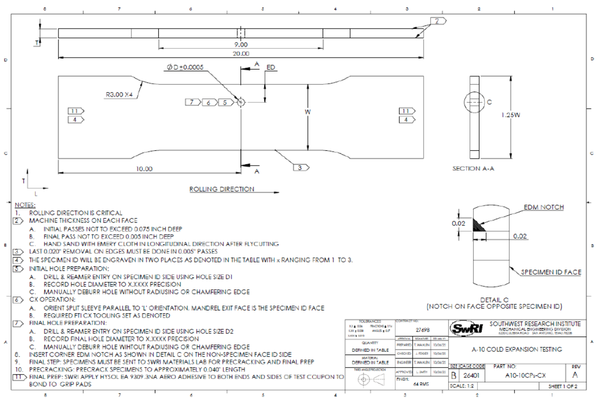


Location	Thickness, in.	Hole Diameter, in.	Hole Offset, in.	Test Type	Replicates
	0.125	0.249	0.500	Baseline	3
				Cx	3
	0.410	0.501	1.690	Baseline	3
				Cx	3
	0.394	0.501	1.040	Baseline	3
				Cx	3
FALSTAFF	0.250	0.250	2.000	Baseline	3
				Cx	3

New A-10 Cx Testing, Variable Amplitude Tests

- Input Data
  - Geometry
    - Various (see table)
  - Material
    - Various (see table)
  - Starting flaw
    - Notched, pre-cracked, and final reamed
  - Cx conditions
    - Baseline non-Cx and Cx holes
  - Loading
    - Variable amplitude

Material	Location	Thickness, in.	Hole Diameter, in.	Hole Offset, in.	Test Type	Test Replicates	RS Replicates
7075-T76511 extrusion		0.125	0.249	0.500	Baseline Cx	3 3	2
7075-T76 sheet		0.190	0.438	1.000	Baseline Cx	3 3	2
AMS 6526		0.190	0.438	0.830	Baseline Cx	3 3	2
2024-T351 plate		0.200	0.197	0.500	Baseline Cx	3 3	2
2024-T351 plate		0.208	0.202	0.470	Baseline Cx	3 3	NA
2024-T3511 extrusion		0.260	0.187	0.680	Baseline Cx	3 3	2
2024-T351 plate		0.410	0.501	1.690	Baseline Cx	3 3	NA
2024-T3511 extrusion		0.394	0.501	1.040	Baseline Cx	3 3	NA
7075-T351 plate		0.245	0.438	1.050	Baseline Cx	3 3	2
AMS 6526		0.250	0.438	0.760	Baseline Cx	3 3	2
7075-T651 plate	FALSTAFF	0.250	0.250	2.0	Baseline Cx	3 3	NA
7075-T651 plate	TWIST/ miniTWIST	0.250	0.250	2.0	Baseline Cx	3 3	NA



ERSI - A-10 Round Robin

- Goals
  - As a collective working group, complete blind predictions based on our best practices
  - Compare/contrast predictions vs test results
  - Utilize findings to refine analysis approach and best practices
- Approach
  - Down select dataset to define analysis conditions
  - Establish initial data and analysis approach/approaches
  - As a team, complete blind predictions

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- Down-Selection of Conditions

ERSI Analysis Priority	Location	Spectrum	Max Stress ksi	Stress Ratio R	Material	Thickness in.	Hole Diameter in.	Hole Offset in.	Test Type	Test Replicates
1	A-10 CP 7T	Constant Amplitude	23.00	0.10	2024-T351 plate	0.410	0.501	1.690	Baseline	3
3									Cx	3
2		Constant Amplitude	25.00	0.15	7075-T651 plate	0.250	0.250	2.000	Baseline	3
4									Cx	3
		A-10 Spectrum		N/A	7075-T76511 extrusion	0.125	0.249	0.500	Baseline	3
									Cx	3
		A-10 Spectrum		N/A	7075-T76 sheet	0.190	0.438	1.000	Baseline	3
									Cx	3
		A-10 Spectrum		N/A	AMS 6526	0.190	0.438	0.830	Baseline	3
									Cx	3
		A-10 Spectrum		N/A	2024-T351 plate	0.200	0.197	0.500	Baseline	3
									Cx	3
		A-10 Spectrum		N/A	2024-T351 plate	0.208	0.202	0.470	Baseline	3
									Cx	3
		A-10 Spectrum		N/A	2024-T3511 extrusion	0.260	0.187	0.680	Baseline	3
									Cx	3
5		A-10 Spectrum		N/A	2024-T351 plate	0.410	0.501	1.690	Baseline	3
8									Cx	3
		A-10 Spectrum		N/A	2024-T3511 extrusion	0.394	0.501	1.040	Baseline	3
									Cx	3
		A-10 Spectrum		N/A	7075-T351 plate	0.245	0.438	1.050	Baseline	3
									Cx	3
		A-10 Spectrum		N/A	AMS 6526	0.250	0.438	0.760	Baseline	3
									Cx	3
6		FALSTAFF		N/A	7075-T651 plate	0.250	0.250	2.000	Baseline	3
9									Cx	3
7		TWIST/miniTWIST		N/A	7075-T651 plate	0.250	0.250	2.000	Baseline	3
10									Cx	3

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- Conditions
  - Materials
    - 2024-T351 and 7075-T651
  - Spectrum
    - Constant and variable amplitude
    - A-10 wing spectrum, FALSTAFF, and miniTWIST
  - Residual stress
    - Baseline and Cx conditions
  - Test replicates
    - Typically (3) each condition
  - Additional information
    - Post-test fractography for each coupon

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- Approach
  - Phase I: Baseline non-cx conditions, CA loading (**complete**)
    - Complete predictions & compare/contrast relative to test data
    - Update any analysis inputs, as required
  - Phase II: Cx conditions, CA loading (**in review**)
    - Complete predictions & compare/contrast relative to test data
    - Evaluate life and crack shape evolution
    - Revisit residual stresses and implementation approach, as necessary
  - Phase III: Baseline non-cx conditions, VA loading
    - Complete predictions & compare/contrast relative to test data
    - Review crack retardation and define approach for Cx conditions
  - Phase IIII: Cx conditions, VA loading
    - Complete predictions & compare/contrast relative to test data
  - Document comparisons and associated lessons learned / best practices for all phases

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- **Phase I Summary**
  - Submissions received from 8 participants
  - Results summarized and reviewed with team
- **Phase II Summary**
  - Submissions received from 4 participants
  - Awaiting submissions 1-2 additional participants
  - Results summarized and initial review discussions completed with submitters
  - Currently identifying lessons learned and best practices

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- **Phase I**
  - Baseline non-cx conditions, CA loading
  - Priority #1-2 analyses
- **Phase II**
  - Cx conditions, CA loading
  - Priority #3-4 analyses

ERSI Analysis Priority	Location	Spectrum	Max Stress ksi	Stress Ratio R	Material	Thickness in.	Hole Diameter in.	Hole Offset in.	Test Type	Test Replicates
1	A-10 CP 7T	Constant Amplitude	23.00	0.10	2024-T351 plate	0.410	0.501	1.690	Baseline	3
3									Cx	3
2		Constant Amplitude	25.00	0.15	7075-T651 plate	0.250	0.250	2.000	Baseline	3
4									Cx	3

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- Summary of Submissions

Submission #	Key Modeling Factors						
	Software		Crack Definition		Material Model	Stress Intensity Calculation	Other Factors
	Lifing Software	FE Software	Front Shape	# of Crack Front Points			
1	NASGRO (v 11.0)	None	quarter elliptical	2	Tabular dataset based on data provided	NASGRO CC26 Weight Function for quarter-elliptical corner crack (remote tension). NASGRO TC43 Weight Function for through crack (remote tension)	
2	AFGROW	None	quarter elliptical	2	Tabular dataset based on data provided	AFGROW advanced model	Crack closure factor (Beta R); Harter finite width correction
3	BAMpF w AFGROW (v 5.4.2.25)	StressCheck (v 11.1)	multi-point	21	Tabular dataset based on data provided	BAMpF w StressCheck	
4	SimModeler/MeshSim	Ansys	multi-point	?	Tabular dataset based on data provided	Displacement Correlation Technique	
5	LifeWorks 2020 (v 5.12.3.0)			2	Developed R=0 curve based on a contact stress model.	Proprietary database of tabular lookup for corner crack at a hole	Stress state set at 2 and 3 for 2024-T351 and 7075-T6 materials, respectively.
6	BAMpF w AFGROW (v 5.4.2.25)	StressCheck (v 11.1)	multi-point	21	Tabular dataset from 7075-T6 was utilized (not provided material data)	BAMpF w StressCheck	Surface correction factor of 0.65 gradiated over 20 degrees from surfaces was utilized.
7	BAMpF w AFGROW (v 5.4.2.25)	StressCheck (v ?)	multi-point	6	Tabular dataset based on data provided	BAMpF w StressCheck	
8	CPAT	StressCheck (v 12.0)	multi-point	21	Tabular dataset based on data provided	CPAT w StressCheck	

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- Priority #1 (Baseline non-Cx, CA loading)
  - Coupons CP7T-B-01 through -03
  - Geometry
    - Thickness: 0.410”
    - Width (test section): 4.00”
    - Width (grips): 5.00”
    - Hole Diameter: 0.501”
    - Hole Offset: 1.690”
    - EDM notch and crack on short ligament side
  - Material: 2024-T351plate
    - Source: Kevin Walker’s recently updated tabular lookup

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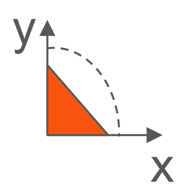
- Priority #1 (Baseline Non-Cx, CA loading)
  - Loading: CA, R=0.1, max stress: 23 ksi
    - Stress represents gross cross-section (no hole) of the gauge section

Block file name:	*CP7T-Baseline-27APR*			
Max Normalized	**Min Normalized**	**Cycles**	Component	Component Cycles
1.00	0.10	1325	CA Block	1325
1.00	0.70	170	Marker	375
1.00	0.10	35		
1.00	0.70	170		
		1700	TOTAL CYCLES	1700

- Starting crack sizes:



X = surface
Y = bore

Coupon CP7T-B-02

EDM	
Surface	**Bore**
0.00000	0.03209
0.02415	0.00000

Crack Front Points

Markerband	
Surface	**Bore**
0.02932	0.00000
0.03217	0.00641
0.03332	0.01698
0.02210	0.03368
0.00528	0.04093
0.00000	0.03965

Coupon CP7T-B-03

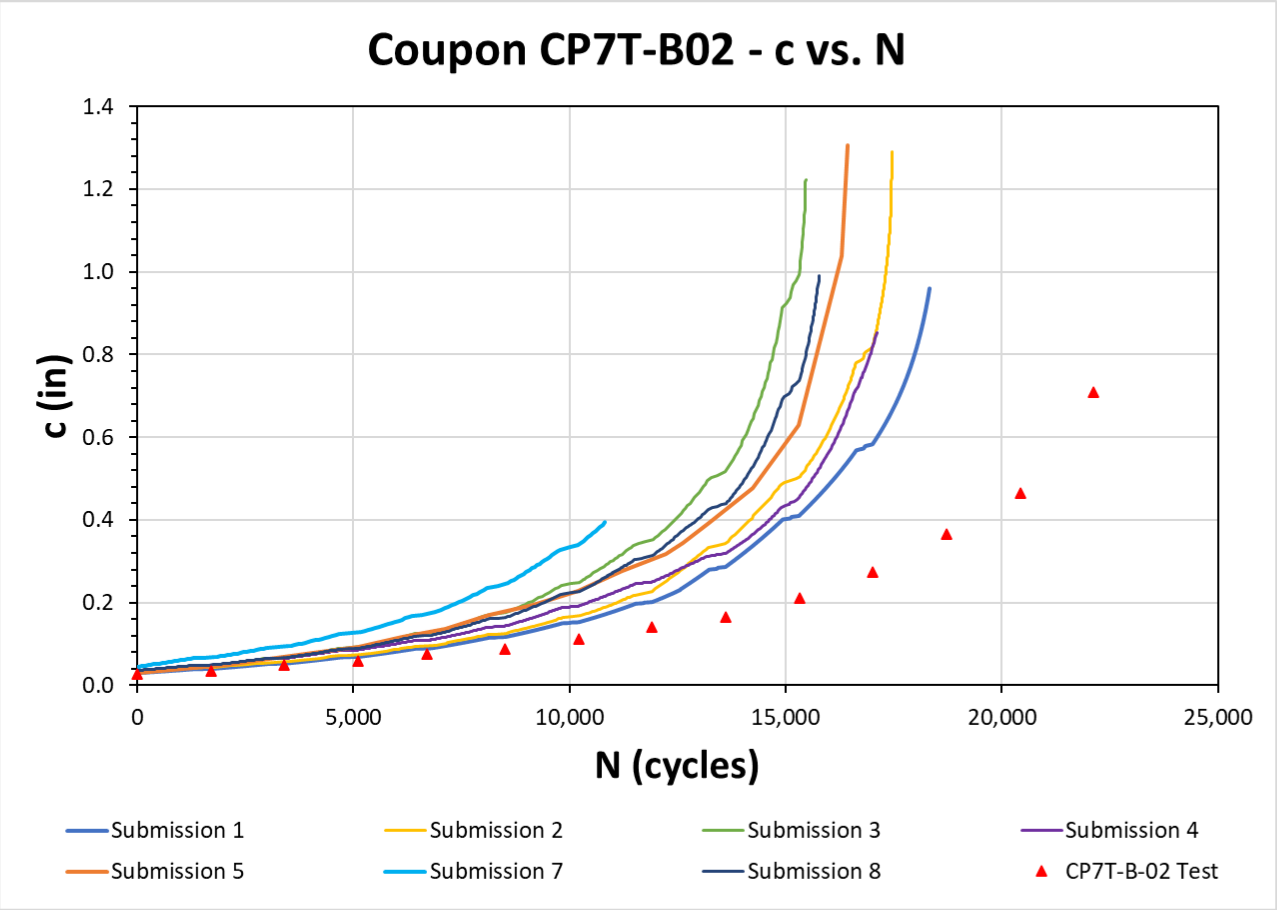
EDM	
Surface	**Bore**
0.00000	0.02363
0.02735	0.00000

Crack Front Points

Markerband	
Surface	**Bore**
0.04407	0.00000
0.04502	0.00343
0.04601	0.00575
0.04461	0.02467
0.04079	0.03723
0.02101	0.05583
0.01464	0.05998
0.00149	0.06248

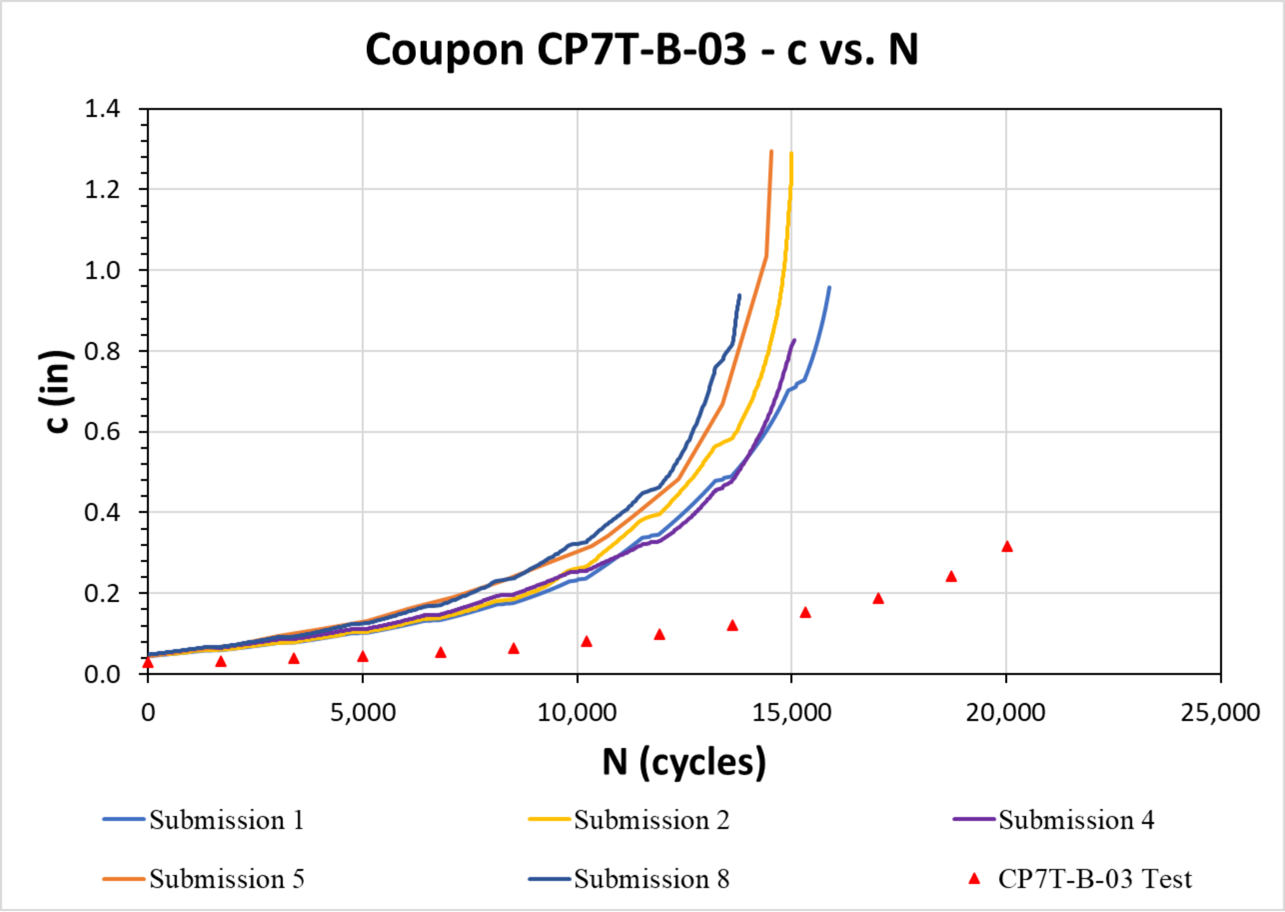
ERSI - A-10 Round Robin

- Priority #1 (Baseline Non-Cx, CA loading)



ERSI - A-10 Round Robin

- Priority #1 (Baseline Non-Cx, CA loading)



ERSI - A-10 Round Robin

- Priority #2 (Baseline Non-Cx, CA loading)
  - Coupons FALSTAFF-B-01 through -03
    - Note: coupon IDs are for consistency with later FALSTAFF spectrum tests, however, these tests are subject to constant amplitude loading
  - Geometry
    - Thickness: 0.250”
    - Width (test section): 4.00”
    - Width (grips): 5.00”
    - Hole Diameter: 0.250”
    - Hole Offset: 2.000”
  - Material: 7075-T651plate
    - Source: Jake Warner’s IFF Round Robin

ERSI - A-10 Round Robin

- Priority #2 (Baseline Non-Cx, CA loading)
  - Loading: CA, R=0.15, max stress: 25 ksi
    - Stress represents gross cross-section (no hole) of the gauge section

Block file name:	*FALSTAFF-MarchOne (BASELINE)*			
Max Normalized	**Min Normalized**	**Cycles by Line**	Component	Component Cycles
1.00	0.15	1025	Primary Block	1025
1.00	0.70	125	Marker Band	275
1.00	0.15	25		
1.00	0.70	125		
		1300	TOTAL CYCLES	1300

- Starting crack sizes:

X = surface
Y = bore

FALSTAFF-B-02

Band	EDM Notch
X	Y
0.00000	0.02499
0.01096	0.01315
0.02342	0.00000

Crack Front Points

X	Y
0.03231	0.00000
0.03411	0.00928
0.03342	0.01631
0.02594	0.03083
0.01257	0.04043
0.00620	0.04016
0.00000	0.03781

FALSTAFF-B-03

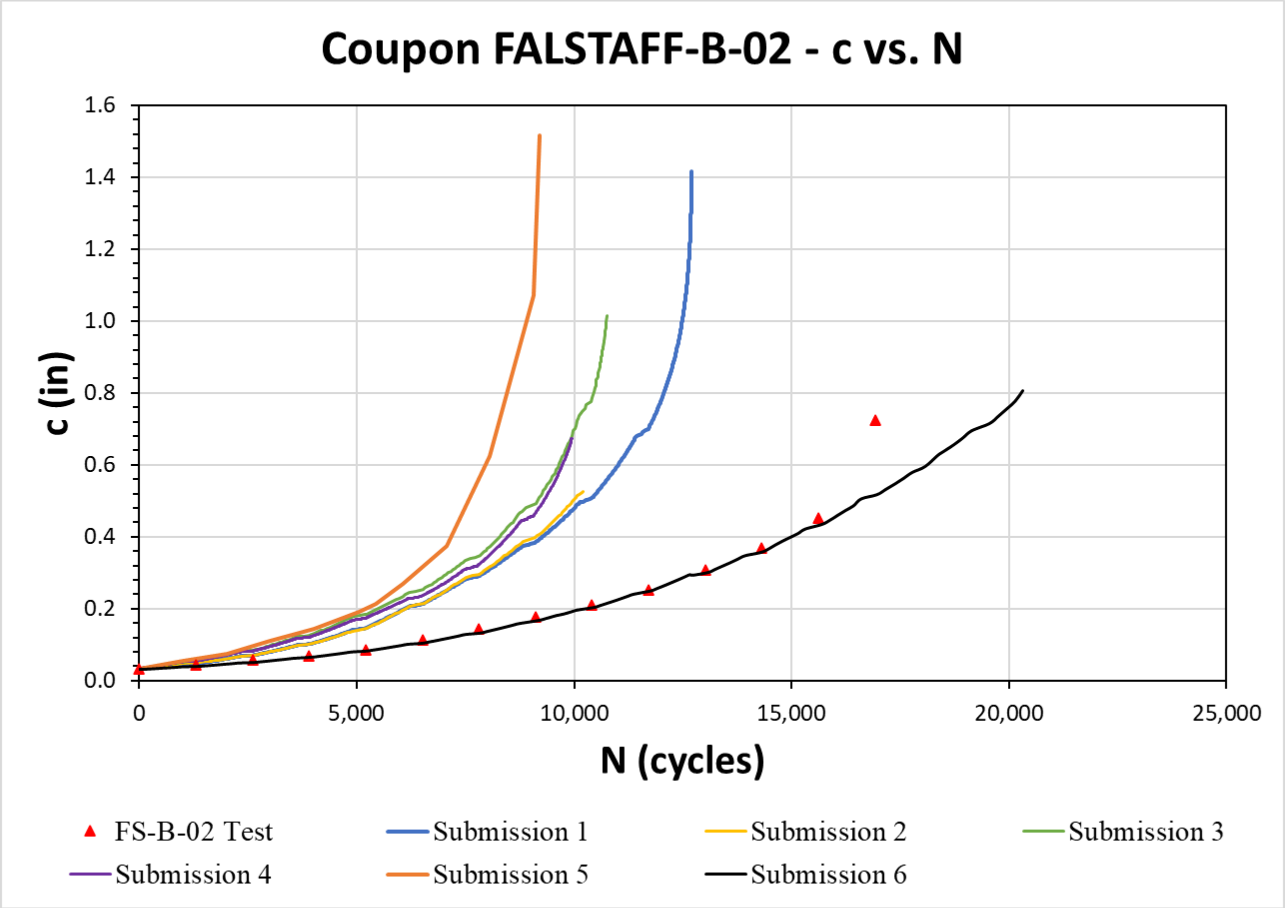
Band	EDM Notch
X	Y
0.00000	0.02260
0.00983	0.01159
0.02206	0.00000

Crack Front Points

X	Y
0.03329	0.00000
0.03449	0.00718
0.03405	0.01014
0.03501	0.01666
0.03054	0.02520
0.02502	0.03257
0.01639	0.04052
0.00534	0.04499
0.00000	0.04417

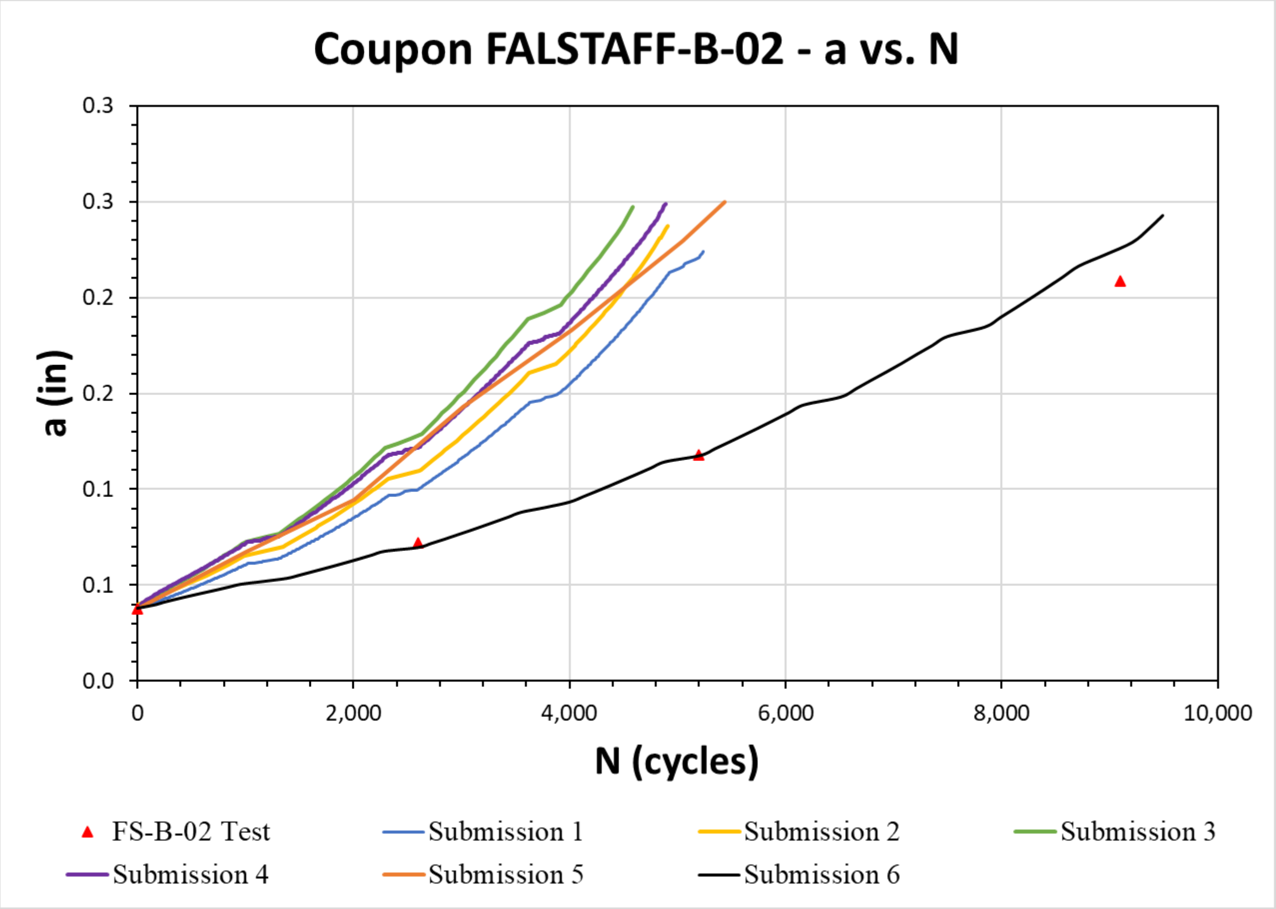
ERSI - A-10 Round Robin

- Priority #2 (Baseline Non-Cx, CA loading)



ERSI - A-10 Round Robin

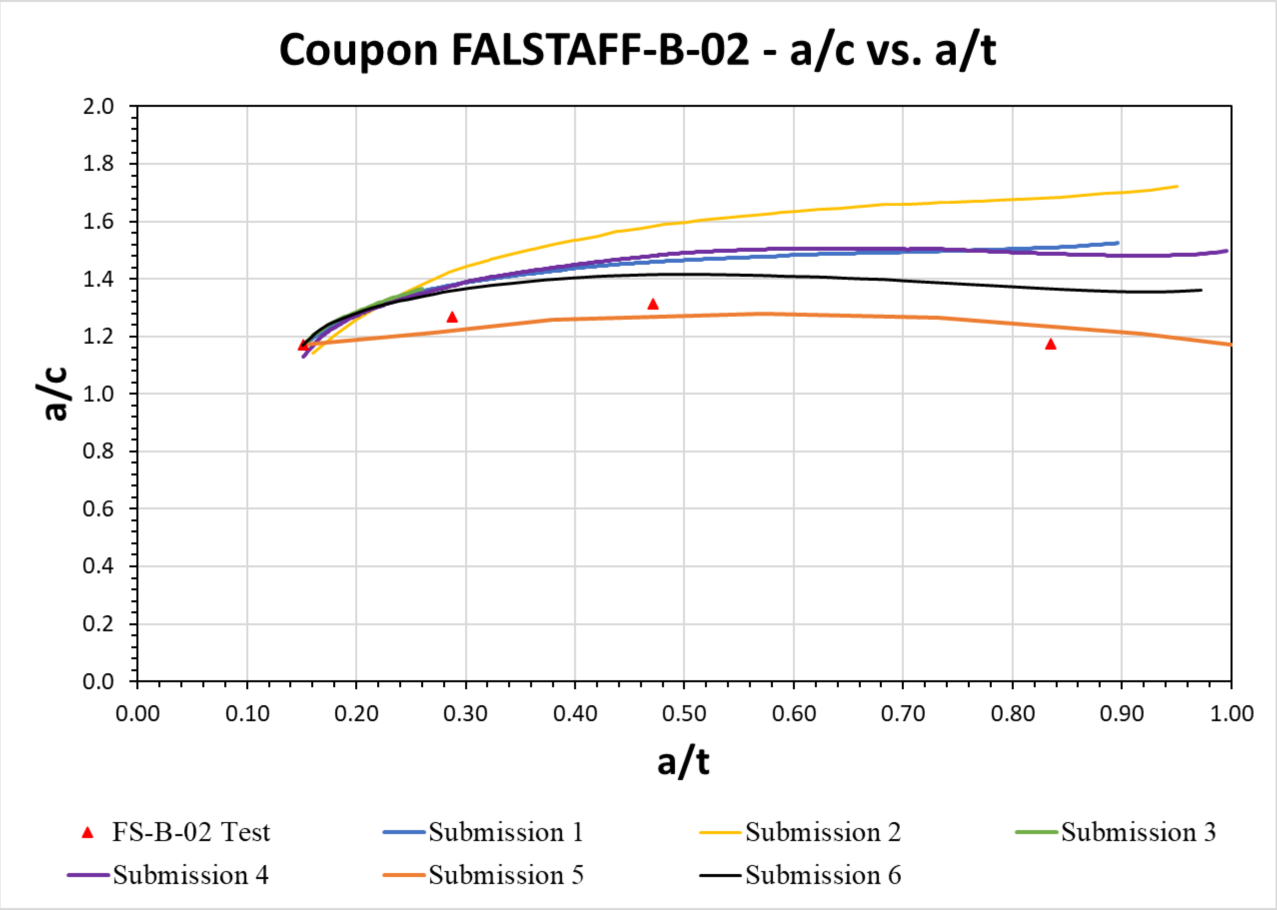
- Priority #2 (Baseline Non-Cx, CA loading)



Working Group on
Engineered Residual
Stress Implementation

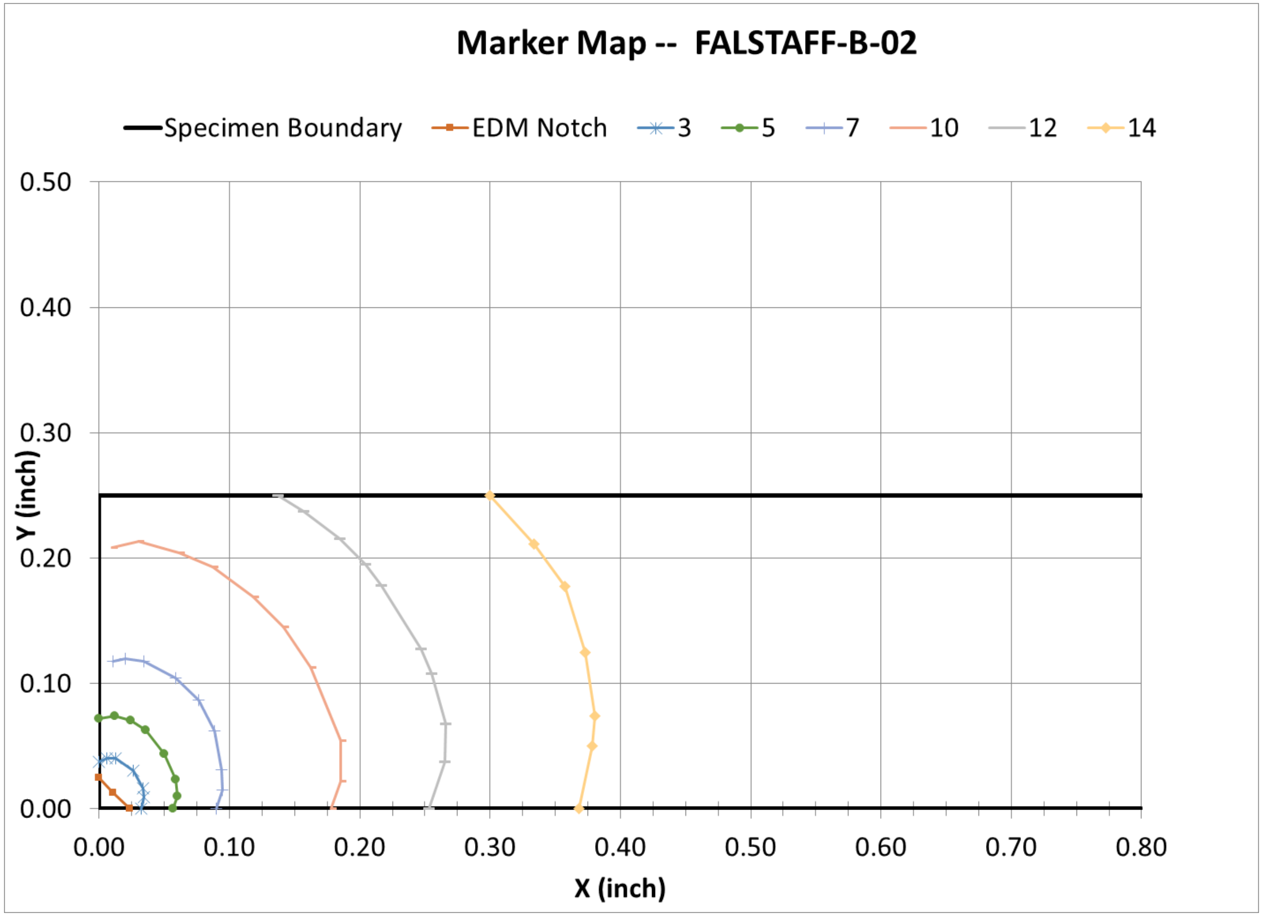
ERSI - A-10 Round Robin

- Priority #2 (Baseline Non-Cx, CA loading)



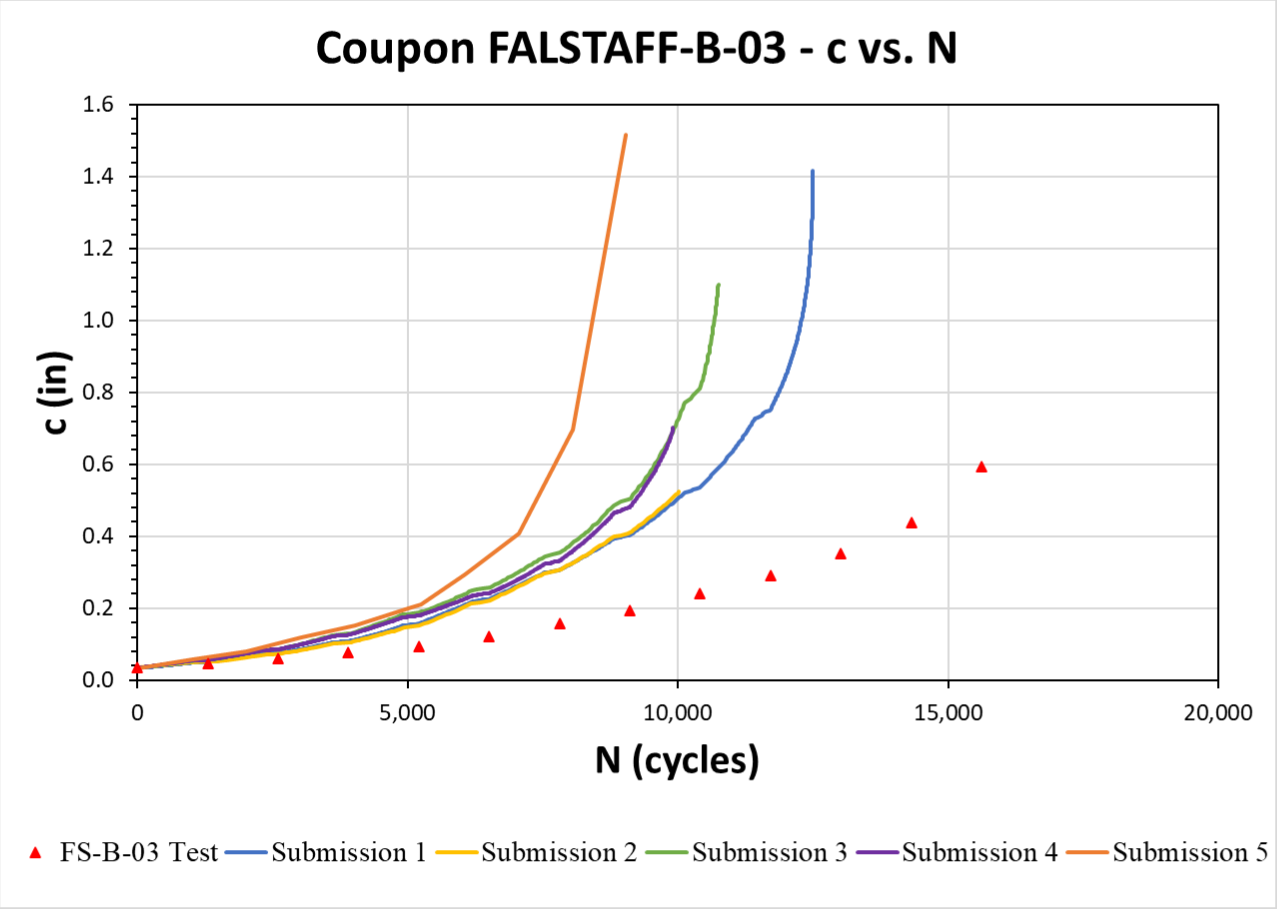
ERSI - A-10 Round Robin

- Priority #2 (Baseline Non-Cx, CA loading)



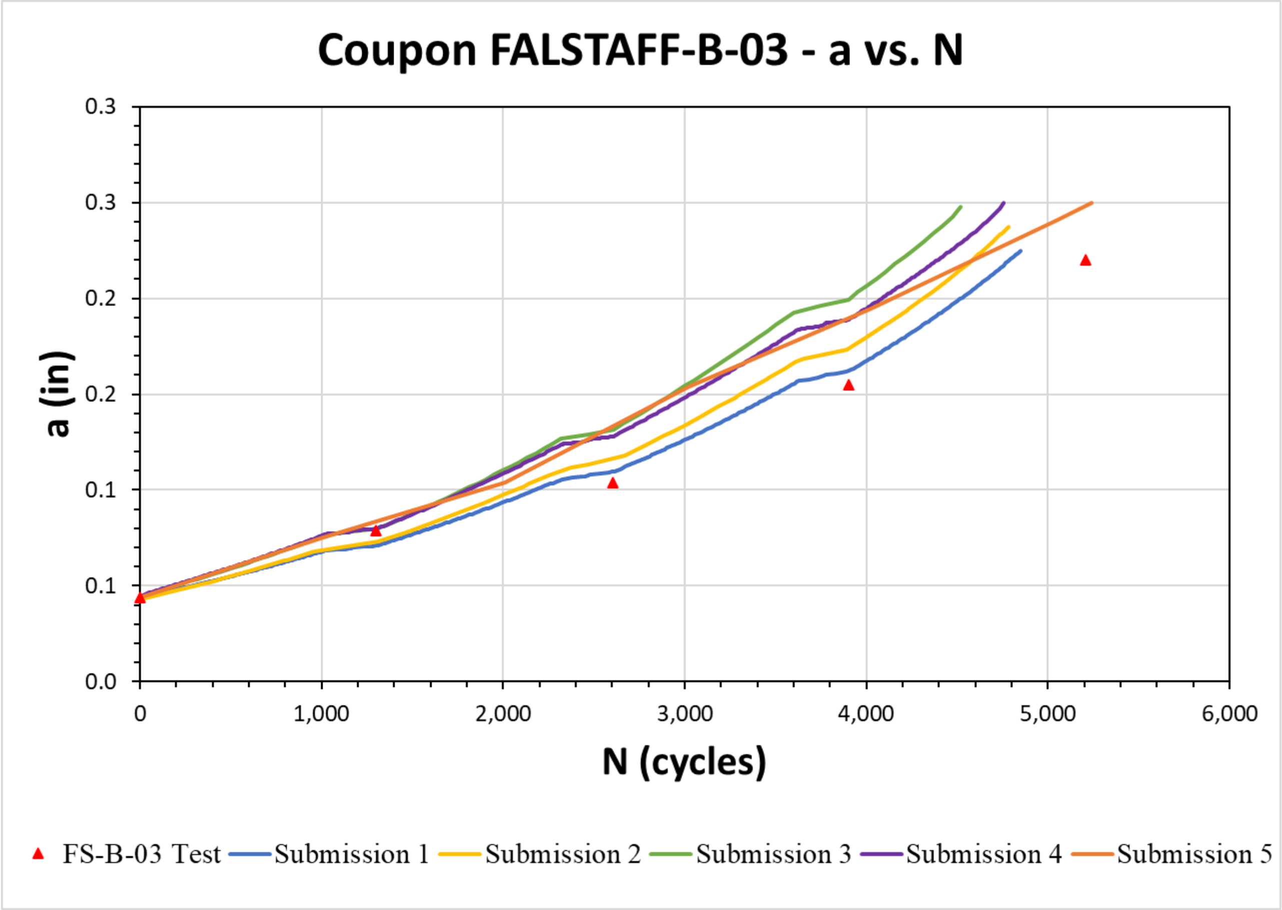
ERSI - A-10 Round Robin

- Priority #2 (Baseline Non-Cx, CA loading)



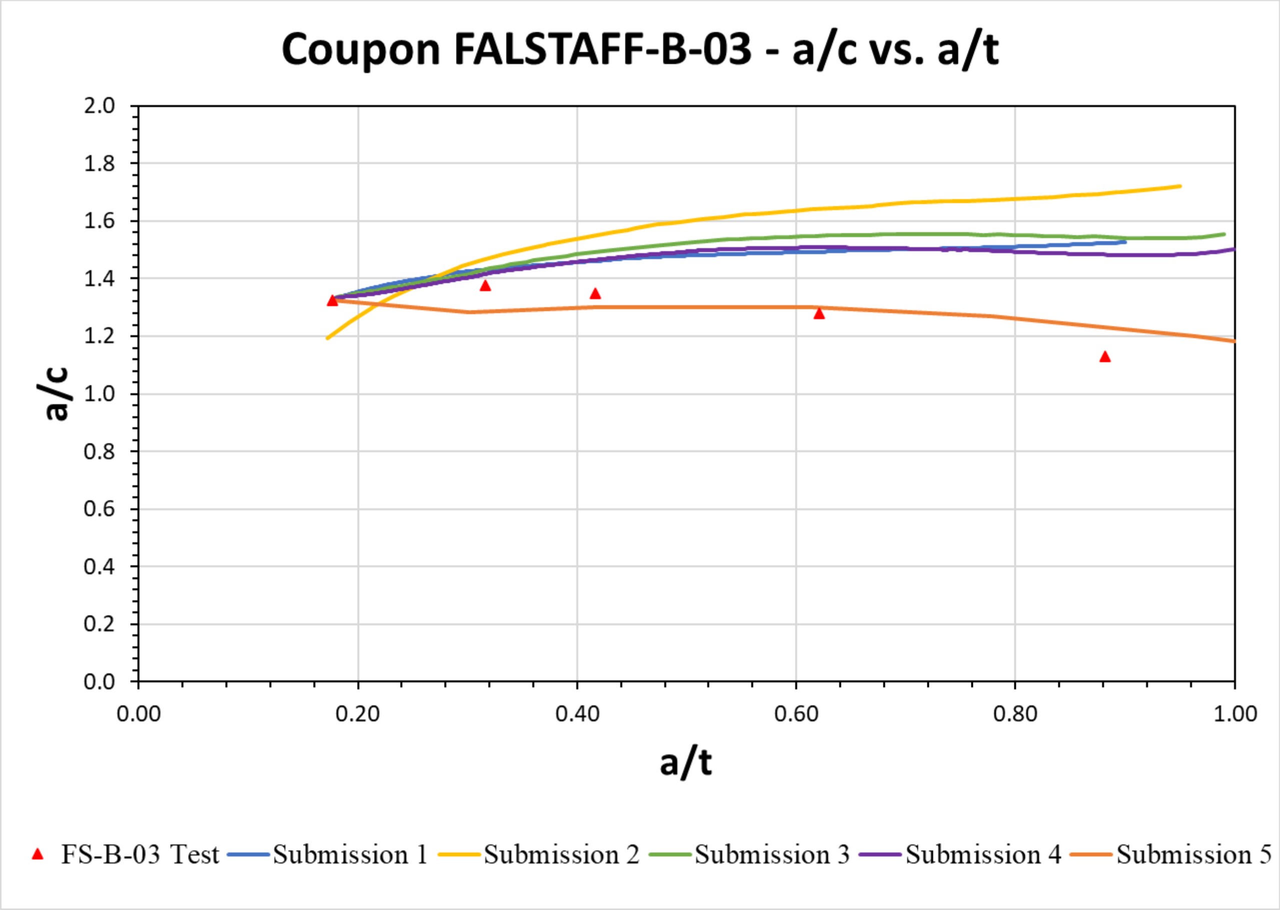
ERSI - A-10 Round Robin

- Priority #2 (Baseline Non-Cx, CA loading)



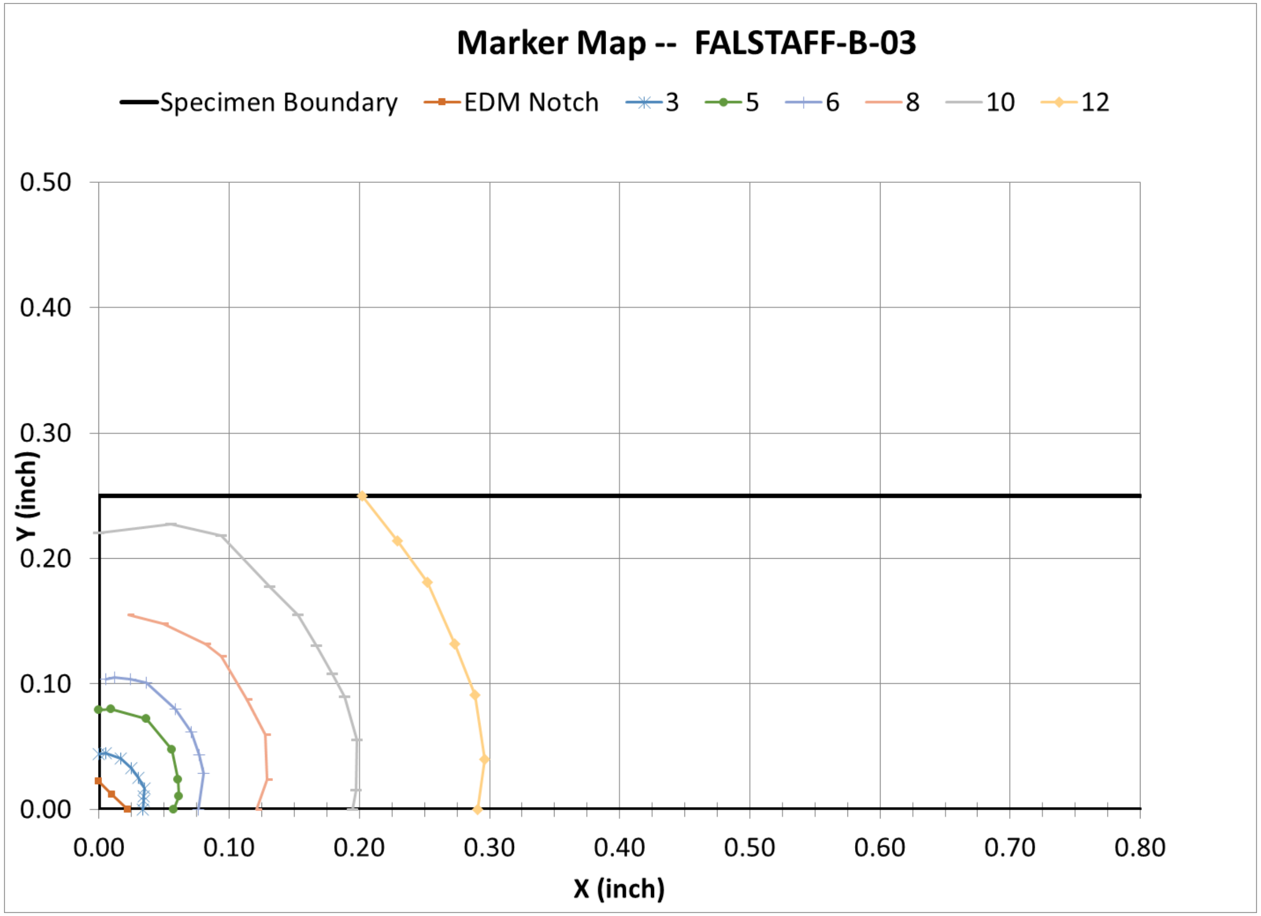
ERSI - A-10 Round Robin

- Priority #2 (Baseline Non-Cx, CA loading)



ERSI - A-10 Round Robin

- Priority #2 (Baseline Non-Cx, CA loading)



ERSI - A-10 Round Robin

- Next Steps
  - Phase I (non-Cx, CA)
    - Summarize primary factors driving differences in analysis predictions
    - Complete postdictions, as necessary
  - Phase II (Cx, CA)
    - Receive remaining submissions
    - Complete comparisons
    - Initiate investigation for analysis differences to support lessons learned and best practices
    - Complete postdictions, as necessary
  - Phase III (non-Cx, VA)
    - Define analysis inputs and approach
    - Initiate Phase III

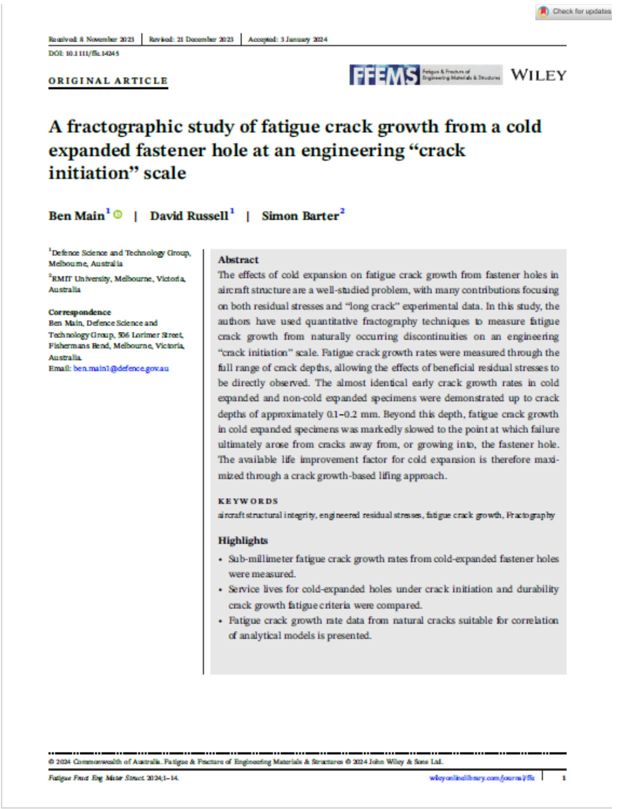
Analysis and Test Ben Main DSTG 7050-T7451 Cx Holes Analysis and Test Review and Lessons Learned

Kevin Walker

ERSI Workshop 13 May 2026

Overview

- Review and re-create Ben Main analysis of naturally occurring cracking at holes in 7050-T7451 specimens under spectrum loading, with and without Cx
- Ben used AFGROW 2 point analysis, so I have re-created that with the latest version of AFGROW, i.e. Version 5.5.3.27 11/29/2005
- I was able to obtain consistent results as Ben, suggesting the methodology is well explained and presented, and appears to be robust
- In doing this, several aspects became evident as being very important for a successful analysis of this kind
- This presentation aims to highlight the important points and lessons learned


Received: 8 November 2023 | Revised: 21 December 2023 | Accepted: 3 January 2024
DOI: 10.1111/ffe.14245
ORIGINAL ARTICLE
FFEMS Fatigue & Fracture of Engineering Materials & Structures WILEY

A fractographic study of fatigue crack growth from a cold expanded fastener hole at an engineering "crack initiation" scale

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[1]Defence Science and Technology Group, Melbourne, Australia
[2]RMIT University, Melbourne, Victoria, Australia
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Ben Main, Defence Science and Technology Group, 506 Lorimer Street, Fishermans Bend, Melbourne, Victoria, Australia.
Email: ben.main1@defence.gov.au

Abstract
The effects of cold expansion on fatigue crack growth from fastener holes in aircraft structure are a well-studied problem, with many contributions focusing on both residual stresses and "long crack" experimental data. In this study, the authors have used quantitative fractography techniques to measure fatigue crack growth from naturally occurring discontinuities on an engineering "crack initiation" scale. Fatigue crack growth rates were measured through the full range of crack depths, allowing the effects of beneficial residual stresses to be directly observed. The almost identical early crack growth rates in cold expanded and non-cold expanded specimens were demonstrated up to crack depths of approximately 0.1–0.2 mm. Beyond this depth, fatigue crack growth in cold expanded specimens was markedly slowed to the point at which failure ultimately arose from cracks away from, or growing into, the fastener hole. The available life improvement factor for cold expansion is therefore maximized through a crack growth-based lifing approach.

KEYWORDS
aircraft structural integrity, engineered residual stresses, fatigue crack growth, Fractography

Highlights
- Sub-millimeter fatigue crack growth rates from cold-expanded fastener holes were measured.
- Service lives for cold-expanded holes under crack initiation and durability crack growth fatigue criteria were compared.
- Fatigue crack growth rate data from natural cracks suitable for correlation of analytical models is presented.

Fatigue Fract Eng Mater Struct. 2024;1–14. wileyonlinelibrary.com/journal/ffe 1

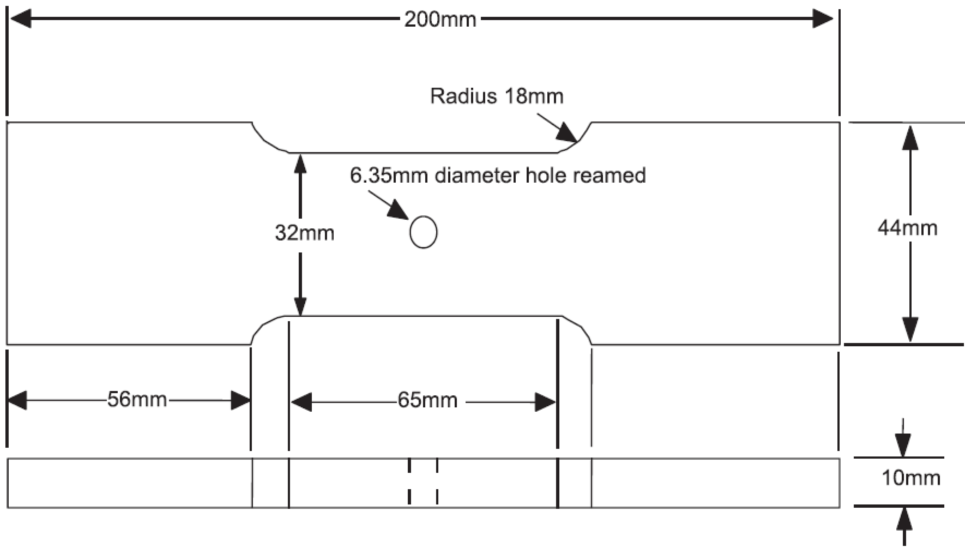
B. Main, D. Russell, S. Barter, A fractographic study of fatigue crack growth from a cold expanded fastener hole at an engineering "crack initiation" scale, Fatigue & Fracture of Engineering Materials & Structures, n/a (2024). https://doi.org/10.1111/ffe.14245

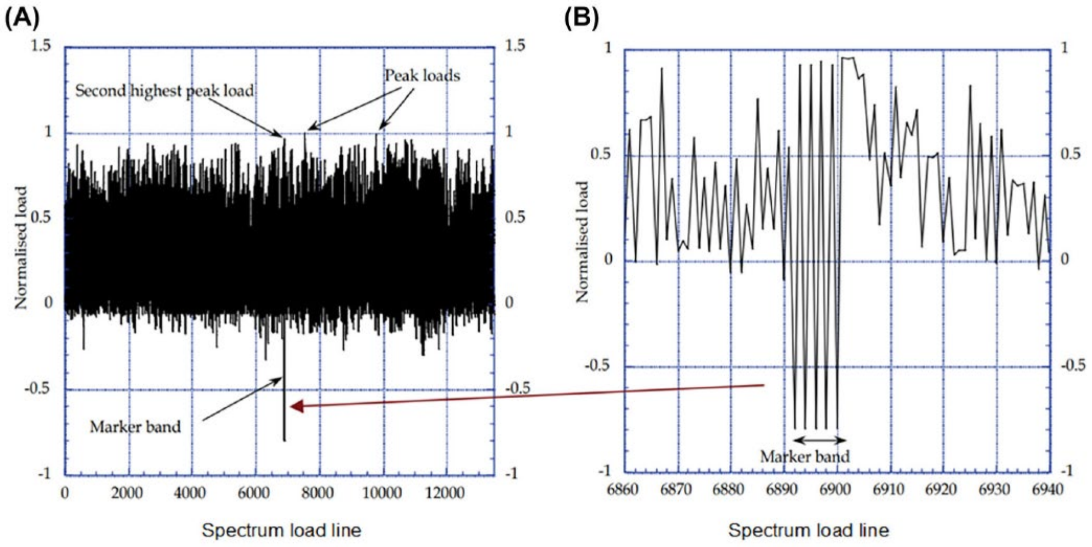
ERSI
ENGINEERED RESIDUAL STRESS IMPLEMENTATION

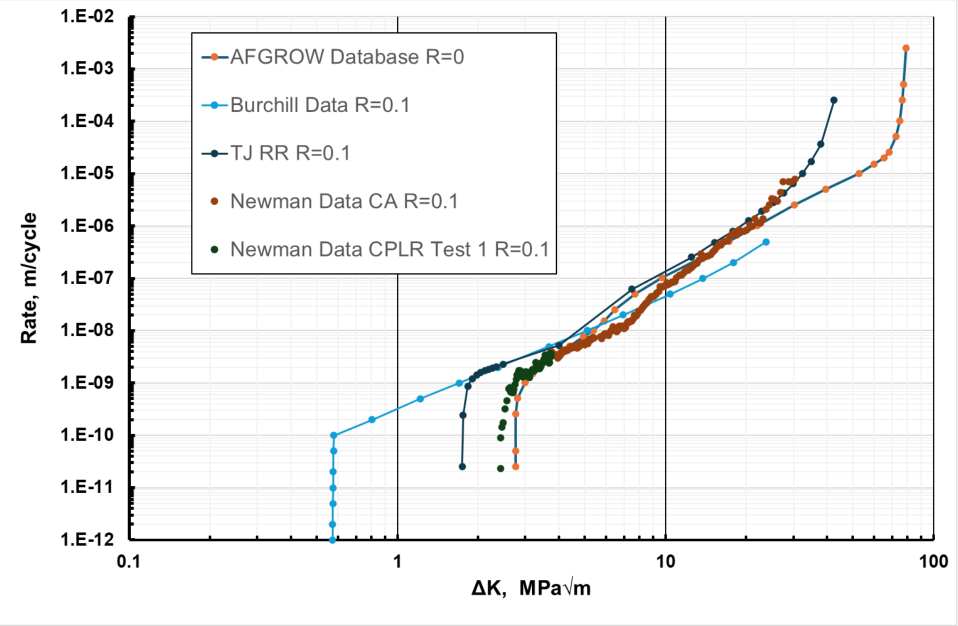
Description of Ben Main Work

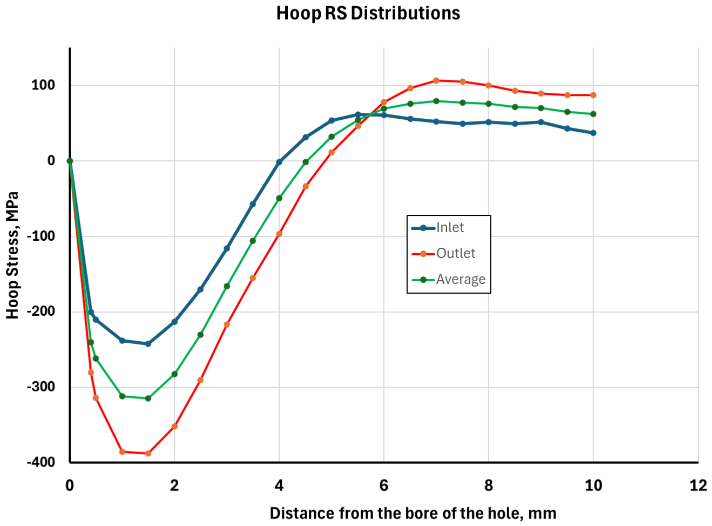
- Ben's work included test specimens from 7050-T7451, 10mm thick, 32mm wide at the test section with a centred 6.35mm dia hole.
- Tests were conducted under spectrum loading with Markerbands, with and without Cx at 4%
- Post test fractography was performed to determine crack growth from naturally occurring cracks
- Analysis was performed using AFGROW. Key points of the AFGROW analysis as follows:
  - Material data and importantly rate vs ΔK data were sourced from other Australian research rather than the library data available in AFGROW
  - Classic SIF model for double surface cracks at a hole was used
  - Residual stresses for the with Cx case is accounted for using the Gaussian integration method

Ben Main Inputs



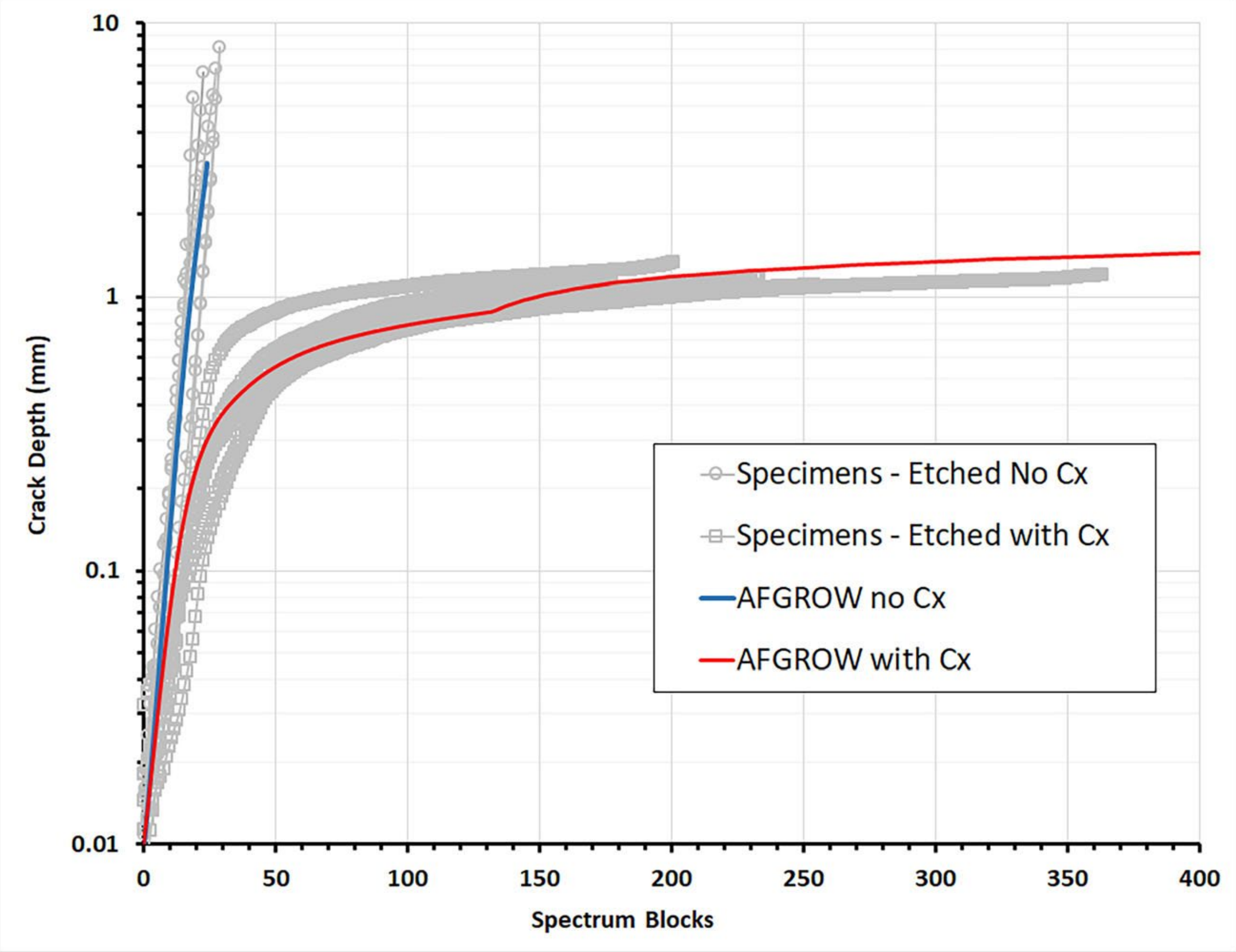


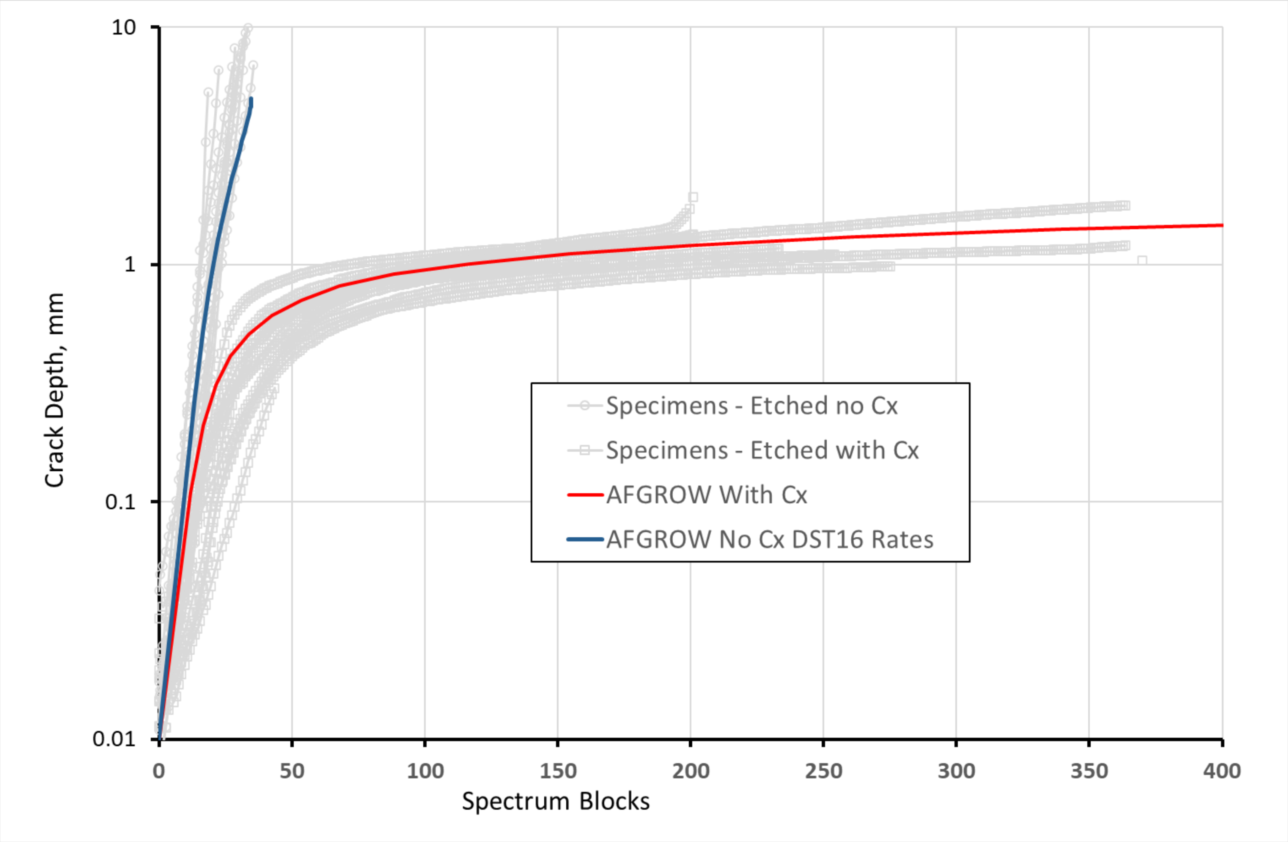




ENGINEERED RESIDUAL STRESS IMPLEMENTATION

Ben Main Vs My Results





ERSI
ENGINEERED RESIDUAL STRESS IMPLEMENTATION

Lessons Learned

- I used Harter Finite Width correction, and applied the crack closure factor (Beta R)
- If I used anything other than the DST rate data with the very low threshold and very low rate data, I got no crack growth from the analysis.
- The XRD RS measurements started at a depth of 0.4mm. So what to use for up to 0.4mm? Important because the analysis starts at a depth of 0.01mm. I assumed ZERO stress at the surface and then linear from there to the data at a depth of 0.4mm.
- All seemed to work well. Why? Good luck? Good science? Main issue seems to be rate data down at extremely low values of ΔK.
- This case included growth from a naturally occurring crack rather than from a notch, which is different to our other cases and is worth further consideration
- The rate data used by Ben includes a much lower threshold than any other data I have seen for 7050-T7451, and was necessary for the analysis to work so well. Another area for further investigation. Potential implications for TJ Spradlin RR from a few years ago.

A-10 IFF Testing & Analysis Program

Overview

- Open literature documents fatigue life benefits due to neat fit and IFF; however, there are no well-established and validated methods to account for the benefits
- A-10 Damage Tolerance Analyses (DTAs) currently do not include any such benefit

Objective

- Develop an empirically validated analytical methodology to quantify the damage tolerance impacts of applicable A-10 fastener installations with neat or interference fits

Current Status

- Phases I and II complete
- Phase IV (FCG Testing) in-progress

Timeline

- Conclude Testing: August 2026
- Phase IV Reporting: September 2026

A-10 IFF Testing & Analysis Program

Phased approach with increasing complexity

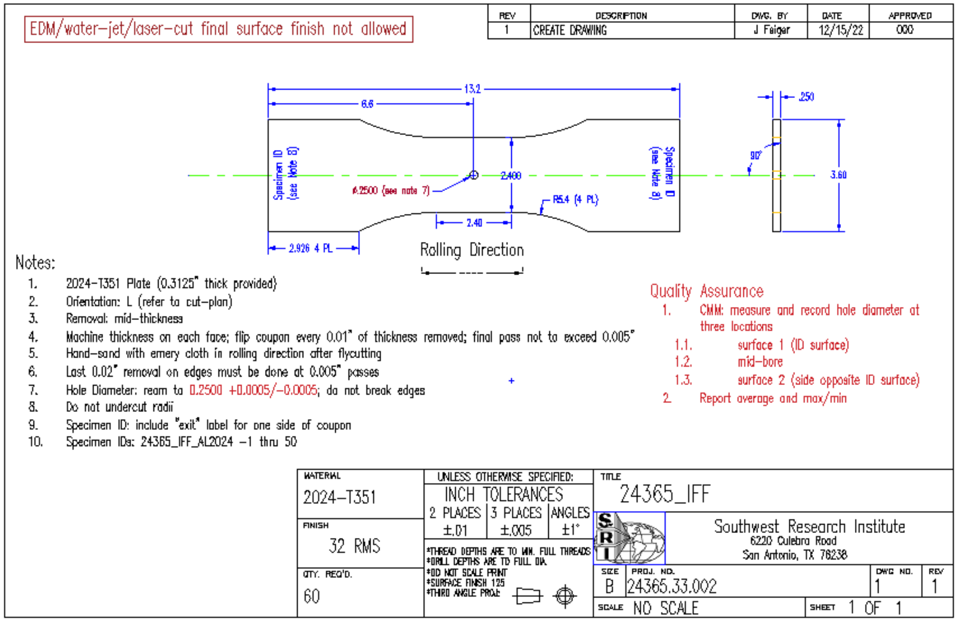
- Phase 1: assessment of as-installed state
  - Simulate and empirically quantify the strain and stress state near a hole in the presence of an interference fit fastener
    - 3 levels of interference
    - 3D nonlinear FE process modeling; DIC and strain gages for surface strain measurements
- Phase 2: fastener installed + remote loading
  - Repeat Phase 1 but with the addition of remote loading and unloading (multiple load levels and interference levels)
- Phase 3: analytical methodology to account for interference fit fasteners during crack growth
  - Perform multi-point fatigue crack growth analyses including interference fit fastener conditions
  - Blind predictions prior to fatigue testing to be performed in Phase 4
- Phase 4: fatigue crack growth testing with interference fit fasteners
  - Perform fatigue crack growth testing of neat fit and interference fit conditions
  - Use fatigue test data for validation and refinement of analytical methodology

Parameter	Levels
Coupon Material	2024-T351 Plate
Pin Material	52100 steel (precision gage pins)
Coupon Thickness	0.25-inch
Nominal Hole Size	0.25-inch
Interference Conditions	Open Hole
	Neat Fit
	0.3% interference
	0.6% interference
	1.2% interference
Strain Monitoring	DIC
	strain gages
Stress Levels (Phase II)	-30
	-10
	0
	10
	20
	30
FCG Testing (Phase IV)	Constant Amplitude Loading
	R= -1, 0.02 and 0.6
	Variable Amplitude/Spectrum Loading
	A-10 CP7 (lower wing skin)

A-10 IFF Testing & Analysis Program

Coupon and Material Information

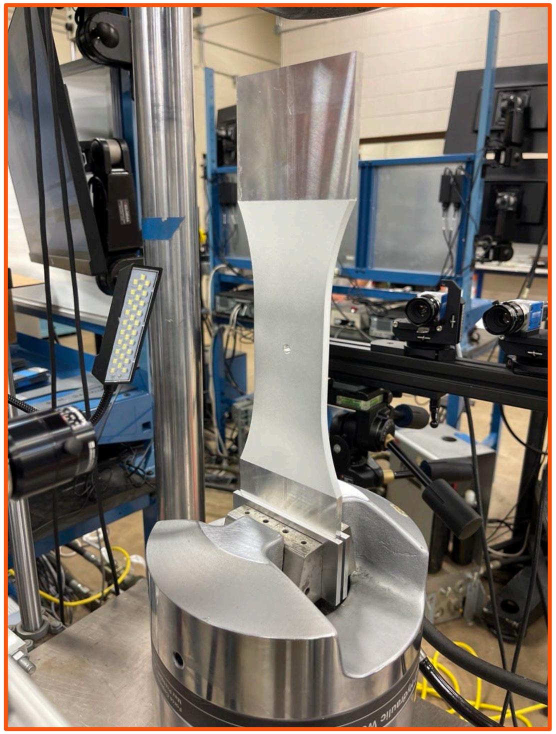
- Coupon design
  - "Dog-bone" with geometric center located 0.25" diameter hole
  - Same geometry used in prior ERS studies
  - Extracted in the L direction at mid-thickness
- Material
  - 2024-T351 plate (0.3125" thick)
  - Material Testing
    + Tensile (5 coupons)
      - ASTM E8
    + FCGR (multiple R values)
      - ASTM E647
      - M(T) geometry



A-10 IFF Testing & Analysis Program

Current Progress (Phases I and II)

- Phase I and II completed
  - Report submitted in June 2025



A-10 FATIGUE AND FAILURE ANALYSIS

INTERFERENCE FIT FASTENER VALIDATION PROGRAM

Contract Number: FA8202–24–F–0009
CDRL: A001

Report Number: SwRI-25-28581-08
Revision Level: DRAFT
Date: 4 June 2025

Southwest Research Institute®
6220 Culebra Road
San Antonio, TX 78238-5166

Prepared by:
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Manager, Structural Integrity
Aerospace Structures Section

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A-10 IFF Testing & Analysis Program

Current Progress (Phase IV – FCG Testing)

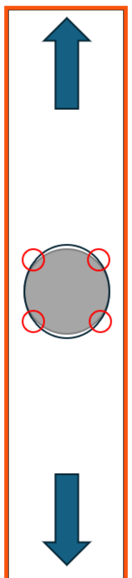
- Test Procedure Developed
  - Finalized and reviewed by IFF Team
- Testing
  - Constant amplitude FCG testing initiated at APES (St. Louis) with Dr. Tom Mills (late summer 2025)
  - R= 0.02 and 0.6
  - Initial results demonstrated long fatigue lives (at planned stress levels) and crack initiation occurring away from the EDM starter notch
    - Remedies:
      - Increase stress levels as needed
      - Move EDM notch to favorable position for the interference coupons (0.3, 0.6, and 1.2%)
- SwRI Testing
  - R= -1 and Variable/Spectrum Loading
    - In-progress
    - DIC to be implemented for variable/spectrum loading tests
- Overall Phase IV status: ~50% complete

Interference condition	No. of Coupons	Load level
Open hole	2	R= -1, 20 ksi
Neat fit	2	
0.3%	2	
0.6%	2	
1.2%	2	
Open hole	1	R= 0.02, 20 ksi
Neat fit	2	
0.3%	2	
0.6%	2	
1.2%	2	
Open hole	1	R= 0.6, 35 ksi
Neat fit	2	
0.3%	2	
0.6%	2	
1.2%	2	
Open hole	1	CP7, 30 ksi
Neat fit	2	
0.3%	2	
0.6%	2	
1.2%	2	

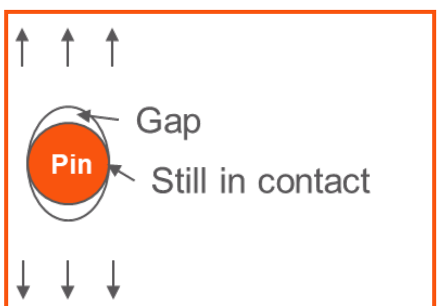
A-10 IFF Testing & Analysis Program

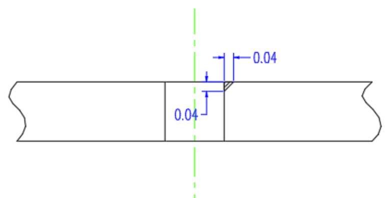
Notch Location Analysis

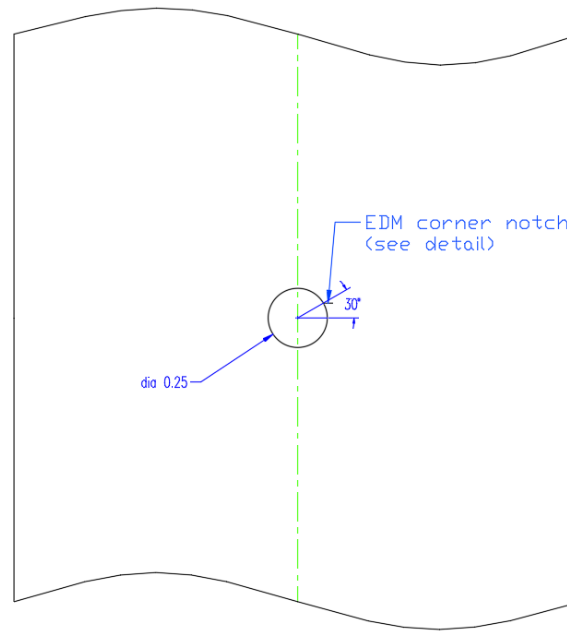
- FEA performed to understand and implement a favorable notch location for the interference conditions (0.3, 0.6, and 1.2% levels)
- Shifted 30° from the 3 o'clock position (now at 2 o'clock)
- Open-hole and neat-fit
  - Notch remains at the 3 o'clock position



Initial FEA







A-10 IFF Testing & Analysis Program

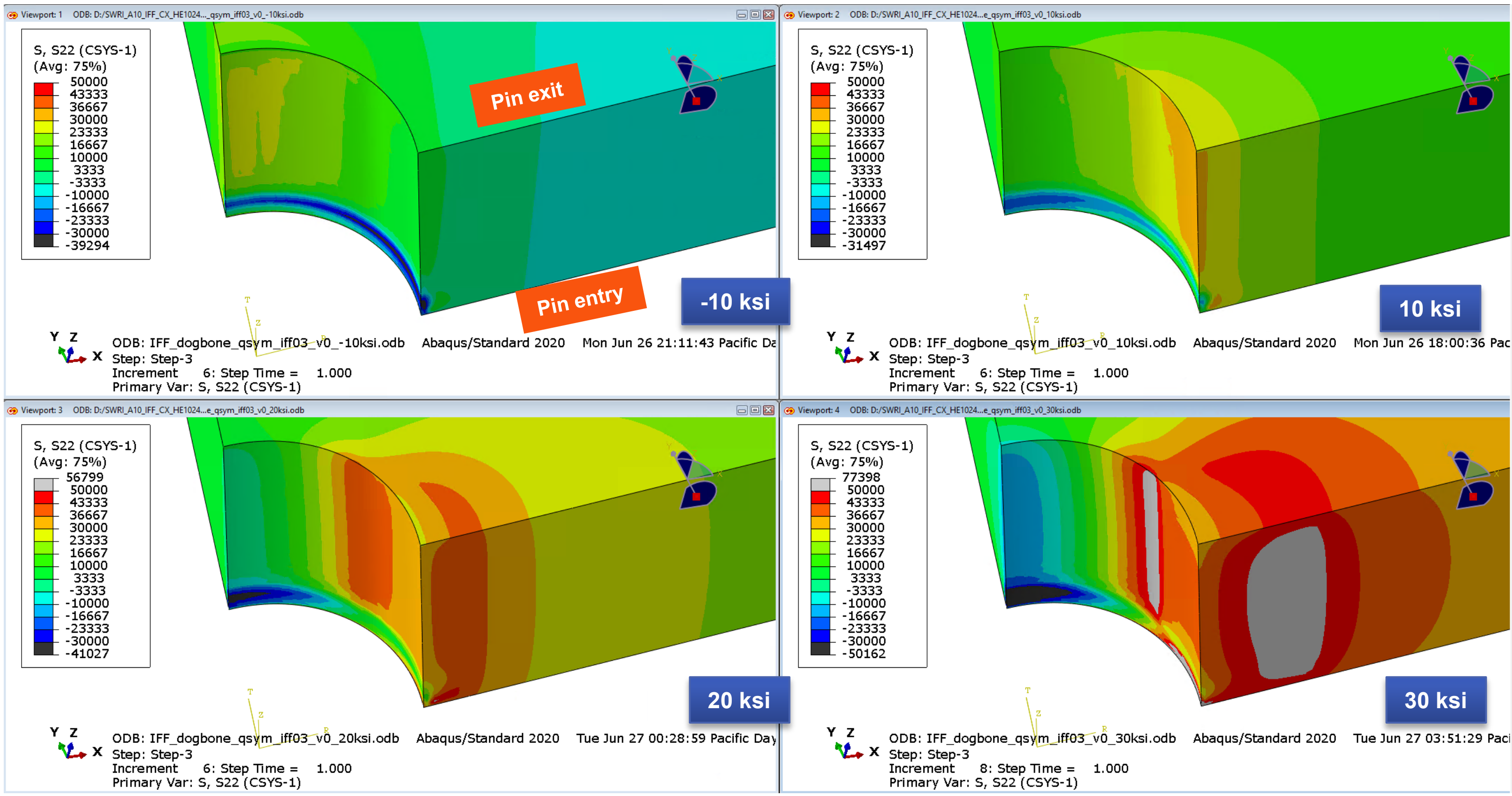
Notch Location Analysis - FEA

- Acknowledgments:
  - Renan Ribeiro (Hill Engineering)
  - Brian Boeke (USAF/Thunderbolt Analytics LLC)
  - Mike Worley (*SwRI*)

0.3% IFF, -10, 10, 20, 30 ksi – install + load step

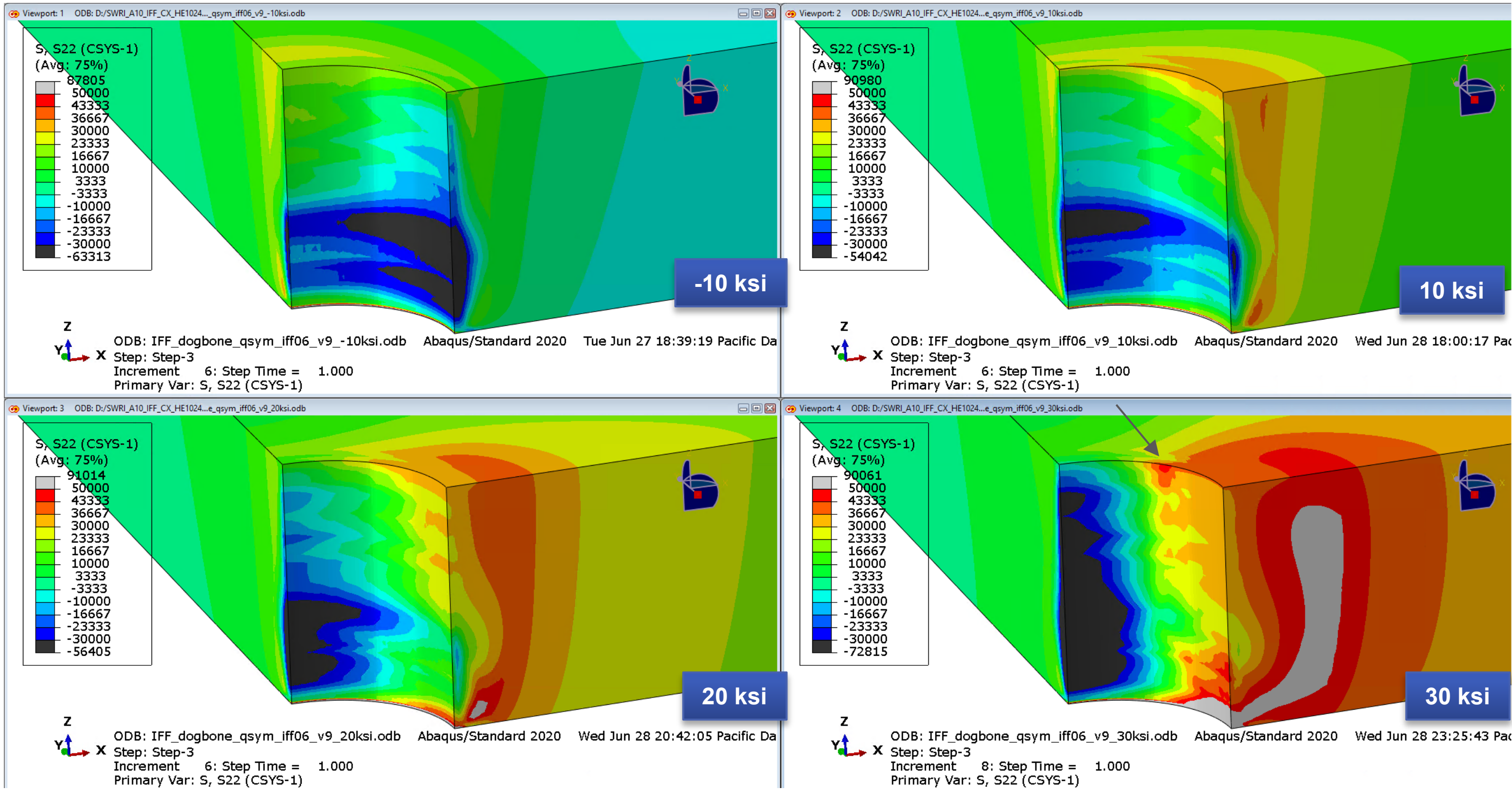
-30 to 50 ksi scale

-10 and 10 ksi don't appear to show high peak stress away from crack plane



0.6% IFF, -10, 10, 20, 30 ksi – install + load step

No clear peak away from crack plane except for 30 ksi condition



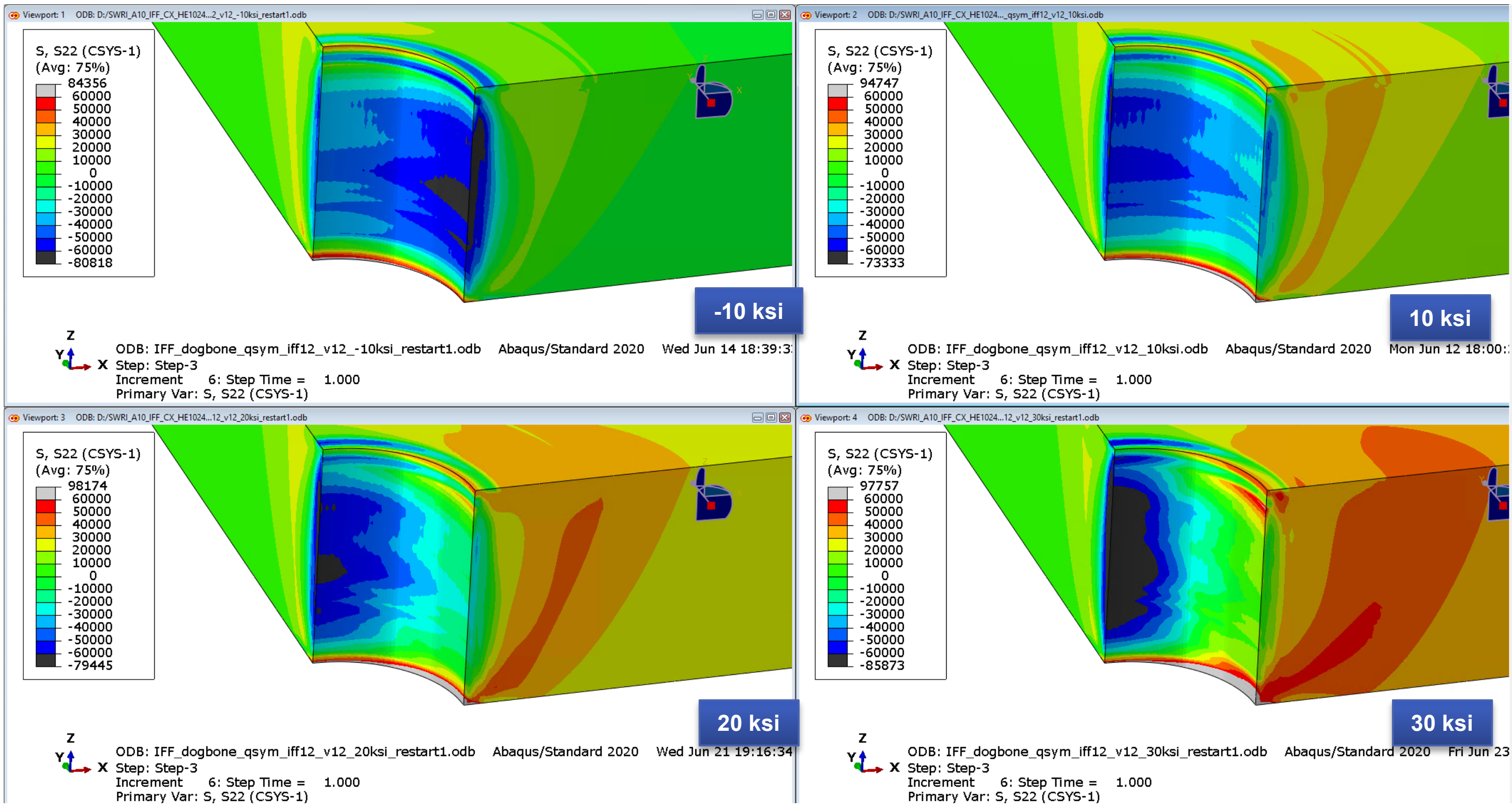
1.2% IFF, -10, 10, 20, 30 ksi – install + load step

-60 to 60 ksi scale

Peak hoop stress away from crack plane not as clear

Larger interference likely reduces the gap between pin and hole

Note that these models had high plasticity near the entry surface

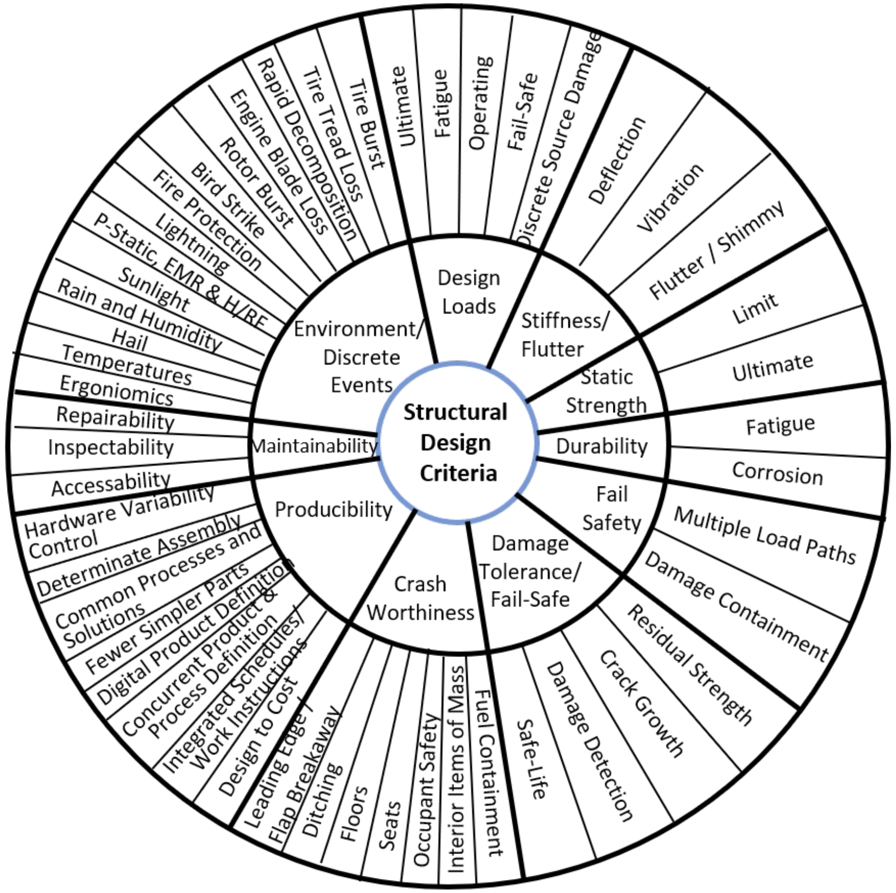


ERSI Lincoln Wheel

Analysis Methods & Testing Refinement

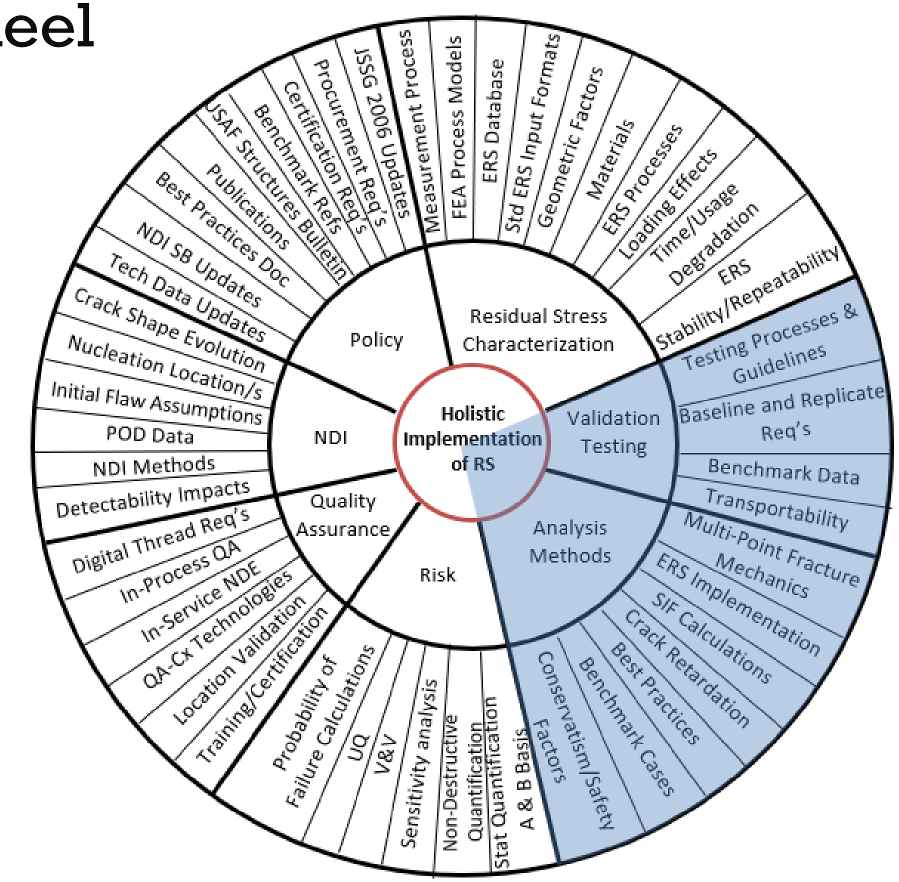
The Original Lincoln Wheel

- A Tool for Evaluating Airworthiness for Structures
  - *Attributed to Dr. John "Jack" Lincoln, Chief/Tech Expert/Tech Advisor for Structures, Aeronautical Systems Center, Wright-Patterson AFB, 1975-2002*



Adaptation for Holistic Implementation of Residual Stress

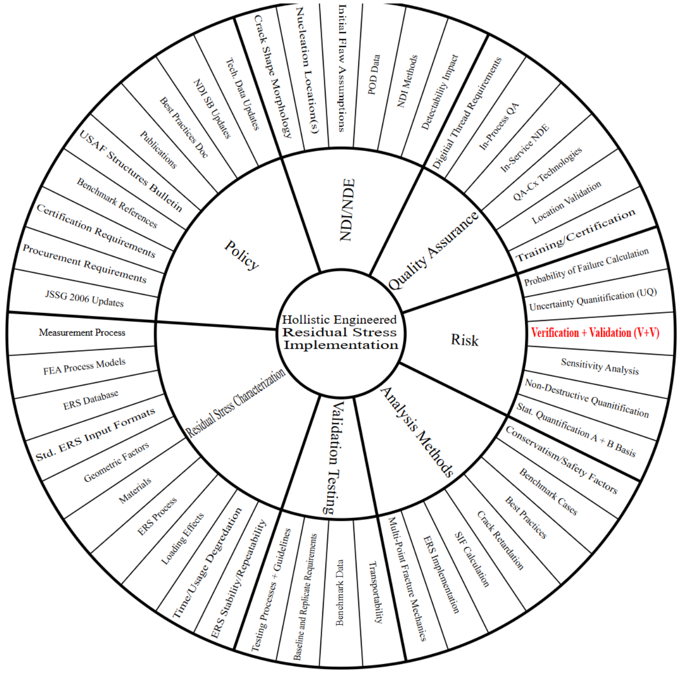
- Originally developed by Bob Pilarczyk, however, detailed review and scrutiny of format, content, etc. has not been completed
- ERSI Analysis & Test Committee collectively kicked off an effort to refine our section of the Lincoln Wheel



Automated Generation of Lincoln Wheel

- Developed an Excel workbook to generate an SVG of the Lincoln Wheel (Adam Morgan)
  - Intent was to build excel workbook that could track document numbers and generate a template file for a new document when a new row is added
  - Selection of the committee and topic allows the tool to generate a Lincon Wheel image (rotated to put the topic at the 3 o'clock position) and highlight the associated topic/committee

Small Step	7.5	degrees	
Center Text	Holistic Implementation of Residual Stress		
Half Width	480		Notes:
Outer Radius	475		Work in-progress, not finished
Middle Radius %	27.5%		
Inner Radius %	9.5%		Fillout [MidRing] table with committees/categories.
Outer 0-degree X-off	955		Sort them in the order you want
Middle 0-degree X-off	744		Recommend filling out [Sort] column for future reorganization
Inner 0-degree X-off	571.2		Fillout [OuterRing] table with topics
Middle Radius	264		Sort them in the order of categories in the [MidRing] Table
Inner Radius	91.2		Recommend filling out [Sort] column for future reorganization
Focus Committee	Risk		
Focus Topic	Verification + Validation (V+V)		
Highlight	FALSE	← Set to false to make image in default position, set to true and Focus topic will be at 3 o'clock	
Offset Angle	0		
	Make Image		



ENGINEERED RESIDUAL STRESS IMPLEMENTATION

Focus Area Summary Templates

- Develop a standardized template to document key focus areas for ERSI
  - Breakdown maturity level, key constraints, questions to resolve, action items and milestones

Testing Processes & Guidelines

Overview		
Focus Item #	1	
Focal		
Maturity Level		

Constraints/Roadblocks	Threshold Criteria	Objective Criteria

Questions to Resolve

Area	Focal/Contract	ECD	Current Status

Action Items

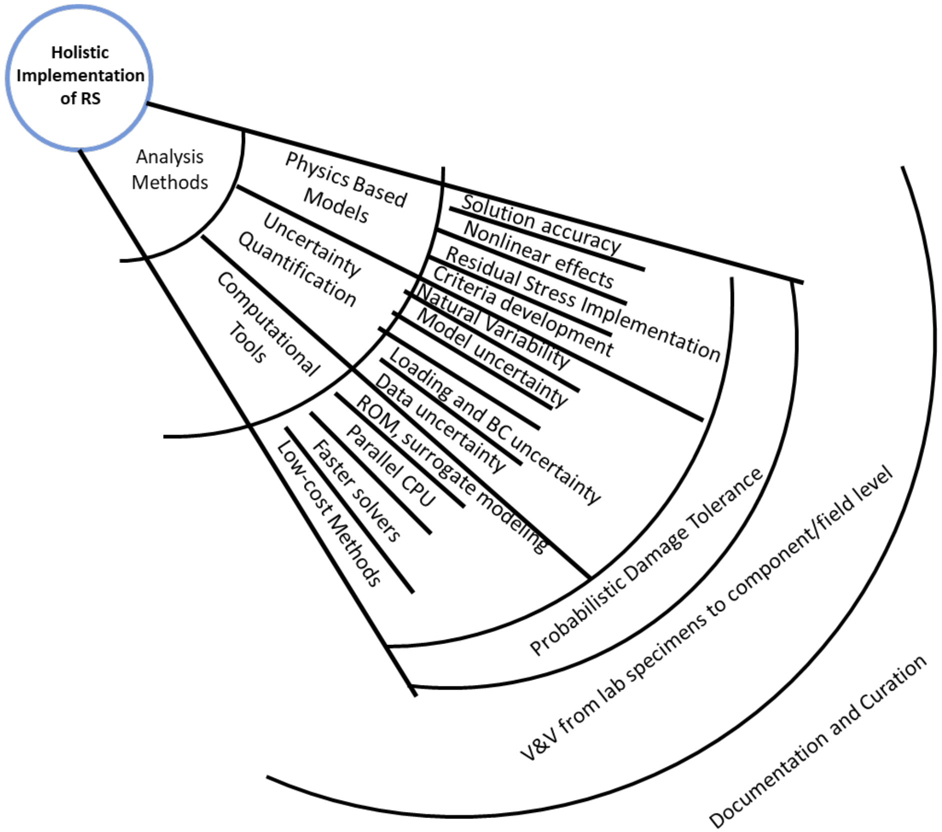
Item	Focal/Contract	ECD	Current Status

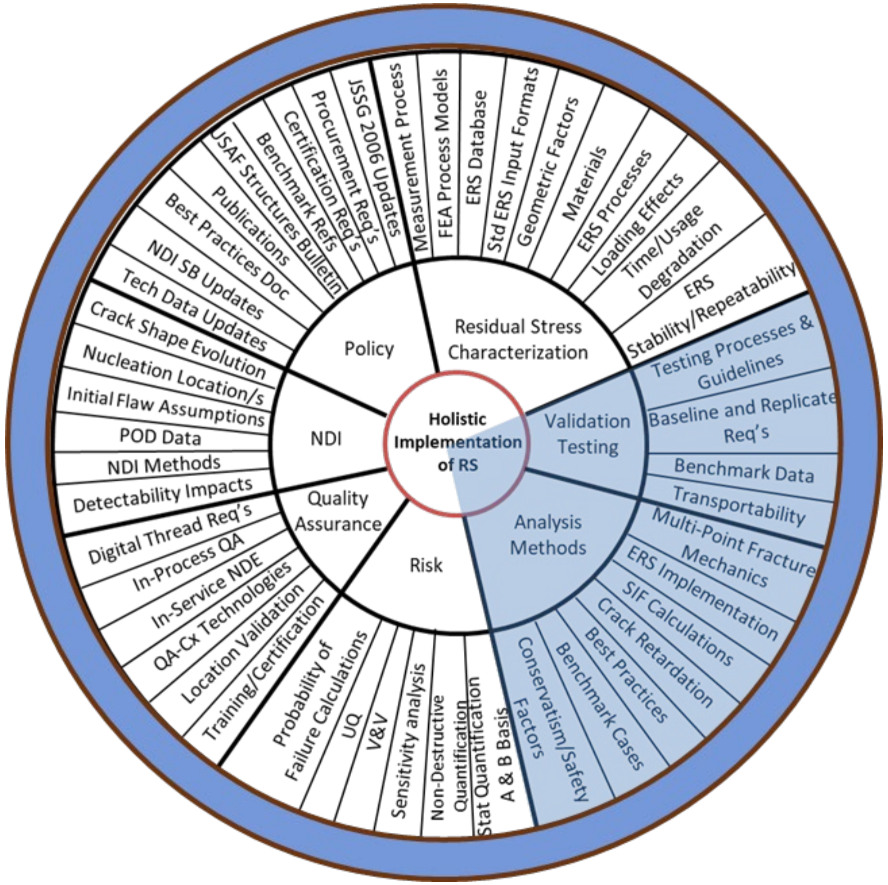
Timeline

2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036

General Comments / Feedback

- Outer Periphery Refinement (Adrian Loghin, Bob Pilarczyk)
  - Utilize the outer ring to document maturity level / closure of each task
  - Additional layers could also be added to highlight overarching aspects that bridge many categories

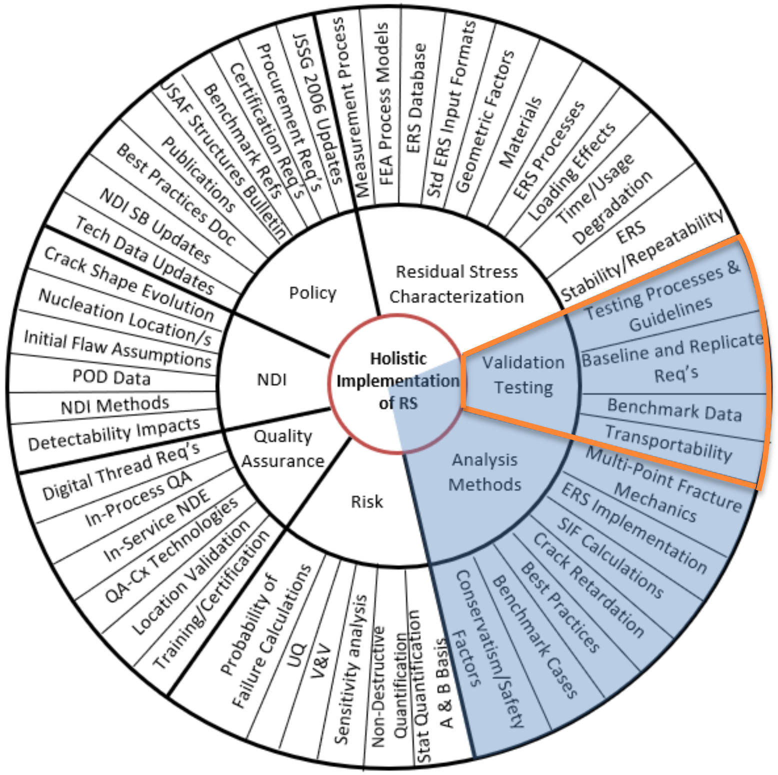




ENGINEERED RESIDUAL STRESS IMPLEMENTATION

Validation Testing

- Purpose (Jeff Bunch): Why perform validation testing? To demonstrate that a cold working process results in a measurable and predictable improvement of structural capability.



ERSI
ENGINEERED RESIDUAL STRESS IMPLEMENTATION

Validation Testing

- Testing Processes & Guidelines (Jeff Bunch)
  - International test orgs (e.g. ASTM, ISO) provide test standards and test guides for performing tests to acquire basic mechanical properties. A number of OEMs, government labs, research institutes, and universities routinely perform tests on full scale components as well as full scale vehicles. Thus, it seems that the intended admonition for this segment of the Lincoln wheel is "don't reinvent the wheel". Rather, leverage existing test experience as well as relevant, existing data. A novel cold working process may use a different tooling, but the types of tests you need to do validate improved material performance have in all likelihood already been performed.
  - Focus on unanswered questions for the process or material that is being validated.
    - Are scale up issues and size effects understood for the process and the intended material system?
    - How close does the final component geometry match existing data?
    - How complex is the final, in service geometry? Is data needed for built up components (i.e. bolted joints) or more complex structures?
  - In developing test plans address necessary deviations from standard processes:
    - Spectrum loading: what is the appropriate spectrum for your application? Can existing test data using a known spectrum be applied to new cases with different spectra?
    - Spectrum truncation is a legitimate variable to adjust to facilitate expedited testing. Is the effect of spectrum truncation as it applies to testing cold work specimens known? (Answering this question **may** be more of an analysis issue than a test validation issue.)

ENGINEERED RESIDUAL STRESS IMPLEMENTATION

Validation Testing

- Baseline & Replicate Requirements (Jeff Bunch)
  - For this segment of the wheel "baseline" requirements should not be confused with basic material data. If you don't have material the material data you need to perform a fatigue analysis or a fatigue crack growth analysis, you will need to obtain that data as a step that is separate and distinct from validation testing.
  - "Baseline" for the Validation Testing segment of the wheel refers to non-cold worked specimens that otherwise match the geometry, material, and manufacturing steps of the cold worked specimens
  - Ideally, the number of baseline replicate tests will match the number of coldworked replicate tests
  - Regarding the number of replicate tests. The reply to this is almost always to perform as many tests as schedule and budget will permit. The justification for budgets and schedule will ultimately depend on the intrinsic risk and consequences of failure.
  - Is your analysis method able to predict the results from component or full scale tests with repeatable consistency?

Validation Testing

- Benchmark Data (Jeff Bunch)
  - The "point of reference" can depend on context.
  - A "benchmark reference case" could be test results for a controlled, and well documented test program whose data is useful for evaluating analysis methods. Building a body of benchmark reference cases is part of the ongoing activities of the ERSI testing group.
  - A "benchmark test" could be a test required to demonstrate the benefit of a new life improvement. This benchmark test specimen would match step for step all material processing and manufacturing steps applied to the actual components.

- Example Filled Out Focus Area

Benchmark Data

Overview

Focus Item #	3	Benchmark data is used to demonstrate capability of life prediction methods. The ASIP approach to benchmark data is for the benchmark to be from specimens that are representative of the final component. This includes using materials and manufacturing processes matching the production component as well as using final test specimens and test loads that match the geometry and loading of the final component.
Focal		
Maturity Level		

Constraints/Roadblocks	Threshold Criteria	Objective Criteria
component testing can be expensive	Knowledge of existing test plans is assessed against ASIP criteria and shortcomings identified.	Roadmap to obtaining benchmark data that satisfies ASIP requirements is in place.

Questions to Resolve

Area	Focal/Contract	ECD	Current Status
When can benchmark data from previous test cases be used for new materials or residual stress applications?			
Does a validated analysis model reduce or eliminate need for full scale component testing?			

Action Items

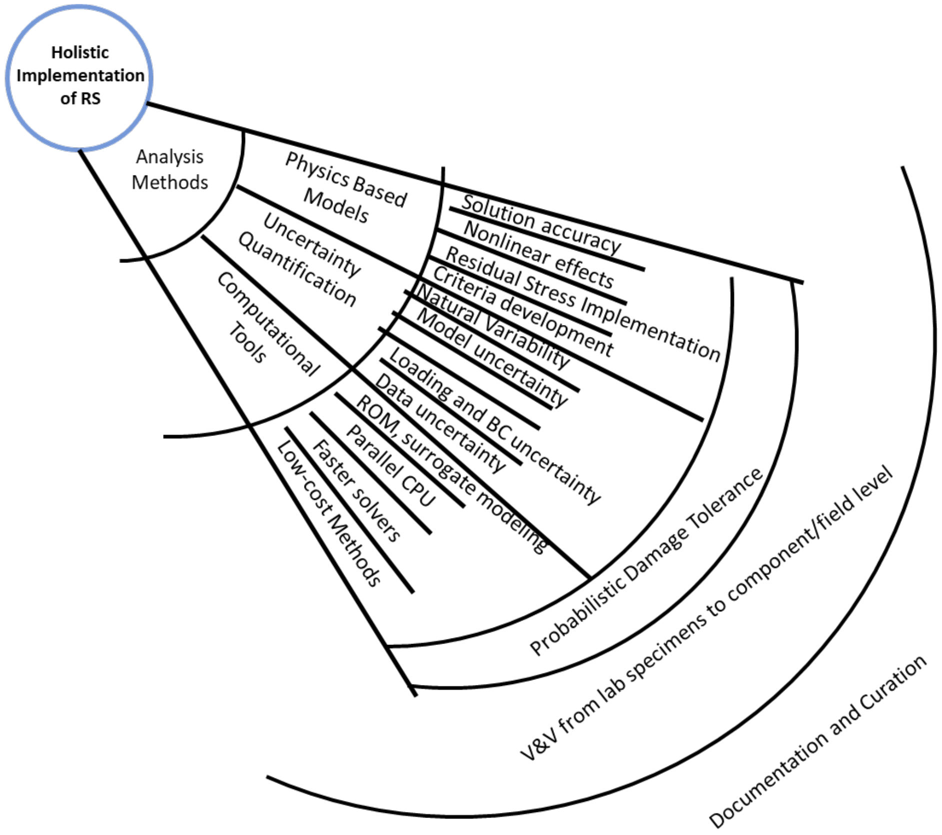
Item	Focal/Contract	ECD	Current Status
From results of Focus item #1 Action item identify and document gaps in existing datasets that would need to be filled to have a complete be			

Timeline

2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036

Analysis Methods

- Multi-Layered Approach (Adrian Loghin)
  - I introduced a layer between Analysis Methods and actual tasks. On top of these methods there is the Probabilistic capability (uses all the other methods). V&V needs to address all needs, from lab specimen to fleet. Documentation and Curation surrounds the entire wheel.



Uncertainty Quantification and Model Validation ofFatigue Crack Growth Prediction

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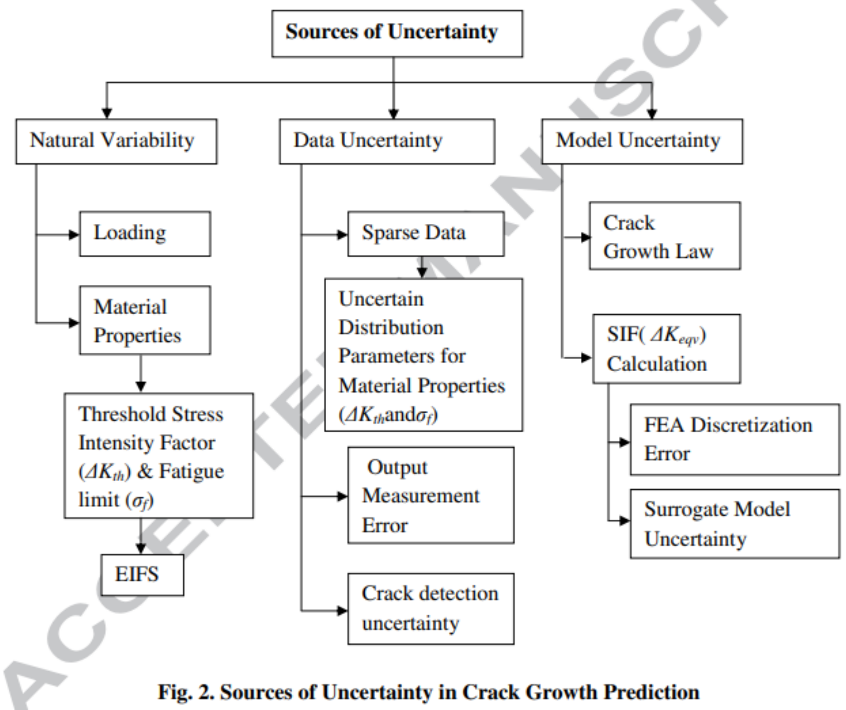
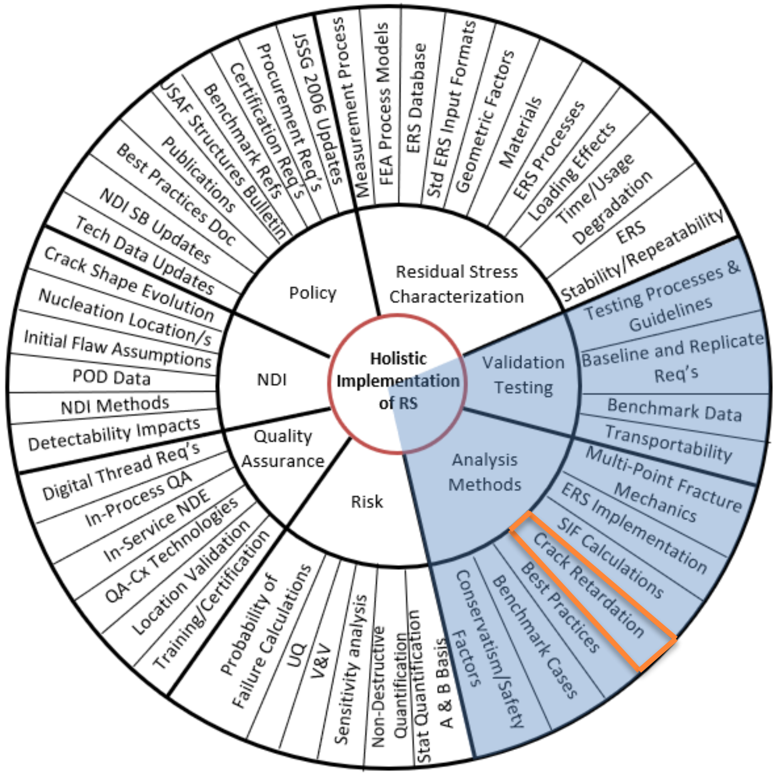


Fig. 2. Sources of Uncertainty in Crack Growth Prediction

Crack Growth Retardation

- Key Factors (Moises Ocasio-Latorre)
  - Closure mechanism (e.g., plasticity induced, roughness induced)
  - Crack opening level (e.g., COD estimate)
  - Plastic zone size
  - Plastic tip constraint level, evolution and loss
  - Crack-growth regime (e.g., short vs. long)
  - Loading sequence effects
  - Crack-tip–notch plasticity interaction



Crack Growth Retardation

- Future Steps (Moises Ocasio-Latorre)
  - Retardation "best practice" playbook from validated case examples
    - Systematically capture examples where strip-yield + variable tip constraint + constraint loss successfully explain observed retardation.
    - Create analysis checklist: what indicators confirm the mechanism, what inputs were critical, and what modeling knobs were essential.
  - Spectrum effects / crack retardation guidelines similar to A-10 multi-point fracture analysis guidelines.
  - Tension–compression modeling verification program
    - Joint verification of strip-yield / constraint-loss predictions under mixed loading using FASTRAN and LifeWorks, explicitly checking how the compression constraint assumption ($\beta \sim 1$) affects predicted retardation.
    - Identify when $\beta \approx 1$ is acceptable vs when it breaks down (likely strongly dependent on geometry/crack size and residual-stress state).
  - Bridging hole-origin spectrum effects with ERS-enabled constraint evolution
    - Extend from middle-tension style cases to fastener-hole crack growth
    - Incorporate ERS states. Include both CA and OL/VA-like sequencing and evaluate how retardation differs between non-CX vs CX-equivalent residual-stress fields.

ENGINEERED RESIDUAL STRESS IMPLEMENTATION

Conservatism / Safety Factors

- Misc. Inputs (Sandro Paulo Daldin)
  - In accordance with the safety standards mandated by civil aviation authorities (such as the FAA and its counterparts, including the Brazilian ANAC, the European EASA, and others), there are some acceptable approaches that may be adopted to address uncertainty within structural analyses:
    - 1 – The use of a sufficiently conservative methodology to account for known and unknown variability and uncertainty, as well as for the inherent simplifications of the models;
    - 2 – The application of defined safety factors to the results of higher-fidelity analyses, in order to account for variability, uncertainty, and model limitations;
    - 3 – A combination of the two approaches described above.
  - The first approach tends to be easier to implement; but generally offers limited gains. The second requires extensive verification and validation efforts; but can result in more significant gains.
  - Under this scenario, the most suitable solution appears to be to initially adopt the first approach to obtain early gains and, as confidence in the analytical methods and results is progressively established through validation and substantiation activities, the methodology may be refined and the applied safety factors gradually reduced, subject to regulatory acceptance.